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INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

D. M. Doty, et al

Fats and Proteins Research Foundation, Inc.

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Investigation of Odor Control in the Rendering Industry

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ABSTRACT

INVESTIGATION OF ODOR CONTROL IN THE TENDERING INDUSTRY

The control of rendering plant odors was investigated, both as to equipment cost and design, and experimental performance. The design studies indicated that scrubbers are the most economical method, and a commercially available spray scrubber system was calculated to be 1/4 as costly as other methods.

The compounds mainly responsible for rendering odors were identified by gas chromatography and mass spectroscopy as well as odor panel tests, and a list of compounds was chosen for experiments. Exploratory bubbler tests were done with a list of scrubbing reagents, and the most promising were further tested in a packed scrubbing column of pilot size. Strong oxidizers, especially sodium hypochlorite, were found to be the most effective on a wide spectrum of compounds. Water is effective on soluble odorants, while alkalies are not very effective. Other agents are effective against specific compounds.

Further tests on a 2-stage scrubber system are suggested to be conducted in a rendering plant.

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INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

1. INTRODUCTION AND SUMMARY

A previous investigation sponsored by the Fats & Proteins Research Foundation, Inc. resulted in identification of some of the compounds in rendering plant odors. This information made it possible to more scientifically investigate the effectiveness of various odor control means, since for the first time the chemical and physical properties of the odor were known. Previously, only subjective evaluations could be made of the effectiveness of various odor control methods, although the dilution method allowed performance to be measured in odor units or reduction ratios.

The objective of this program was to develop an effective and economic means of odor control. Before undertaking laboratory experiments, known and potential odor control methods were compared based on limited data from the literature, and reports of performance and cost from member companies of the Fats & Proteins Research Foundation. This comparison indicated that scrubbing was probably the most economic method, especially if one or more effective scrubbing reagents could be found. Incineration was also feasible, but was more costly for most applications. The study also indicated that commercially available control equipment was not designed on a reliable basis, partly because of the lack of quantitative data on the odorous compounds in rendering odors. Rendering companies were not in a position to rationally select from among the control equipment offered by manufacturers.

Although the experimental work concentrated on scrubbers, the design analysis was extended to several types of incinerators, scrubbers and carbon beds. More novel approaches were also considered but not studied extensively. A design computer program was written for each control method (except carbon beds), and these programs can be used for preliminary estimates of the cost of each method for the particular conditions of any rendering plant. These costs will differ depending on the size of the air stream to be treated; and its concentration, which depends on whether the source is process air or more dilute plant ventilation air. For each control method the computer program estimates the size of equipment needed based on a simplified design method; for example, the design of scrubbers is based on the idea that reagents have been found that react rapidly with the odorants, once they reach the liquid phase, and that the rate of removal is controlled by mass transfer from the gas to the liquid. In the case of incinerators the rate is assumed to be governed by an overall combustion reaction, the rate constants for which are determined as a function of temperature from available plant data. Based on these concepts the programs are able to explore or optimize the operating conditions to find the design having minimum annual cost. Cost data are supplied to each program as input data, and the basis for the cost calculations is given under the description of each program. Both investment amortization and operating costs are included in simple form.

Results of design and cost estimates for each control method are presented in tabular form for a series of air flow rates and odor reduction ratios. Most rendering plants will be able to find a case similar to theirs to obtain a preliminary idea of the control methods available to them. Individual calculations can also be done at reasonable cost.

As a result of the information presented, we can conclude that scrubbers offer the most economical control method, provided that effective reagents can be found. An incinerator may be more economic for a small, highly concentrated process air stream, since removal of the higher concentration only requires incineration at a higher temperature and/or longer contact time. The contact times and temperatures conventionally used for design of such incinerators are inadequate for odor control, however. Catalytic incineration does not appear to be economically competitive.

A novel spray scrubbing system that is commercially available is calculated to control odors at a cost 1/4 that of other available equipment. A typical unit cost is $.16 per 1000-cfm-hr of operation. Previously available spray scrubbers were not effective and the reasons for the improvement are suggested by the calculations. There have been several installations of this type of scrubber in rendering plants; a removal of 85% of odor was reported in one case. Much higher removals would be necessary in practice, and this might be achieved through more rational choice of operating conditions and selection of the best scrubbing liquids. A test of this and a conventional scrubber is proposed for the following year in a rendering plant.

Additional studies were conducted to further identify the compounds responsible for rendering odors. Improvements in gas chromatography and mass spectroscopy made possible the identification of most of the important species. At the same time, odor panel tests were done to determine which peaks are responsible for the main odors. This was done by sampling odors from six plants before and after scrubbers and incinerators. Computer regression of the odor intensity with the peaks present determined which peaks could be responsible for the odors. An effort was then made to identify these peaks by mass spectroscopy. The important peaks and their identifications are given in Table 30. They include various sulfides, disulfides (and probably mercaptans), C4 to C7 aldehydes, trimethyl amine and various C4 amines, quinoline, dimethyl pyrazine and other pyrazines, C3 to C6 acids. Other compounds that are present but are probably not so important as far as odor is concerned are C4 to C7 alcohols, ketones, hydrocarbons, as well as many common aromatic compounds. Some of these compounds contain double bonds.

A list of compounds was selected to represent the important chemical types in the rendering odors. Scrubbing experiments were then done on these pure compounds. Concentrations were measured by chromatograph, by calibrating the area under the chromatograph peak with known amounts of the pure compounds.

Two types of experiments were done. The first was an exploratory experiment, in which one or more odorant compounds was mixed with water in a gas bubbler bottle. An excess of a scrubbing agent was added, air was bubbled through the mixture and the odorant concentration in the air was compared before and after adding the reagent. This method eliminated any reaction rate effect, since the contact time was long. The most promising reagents were then tested using a packed bed scrubber. This scrubber was of standard configuration, with known mass transfer properties. Scrubbing reagents tested included types that have already been used for odor control, plus some not previously tried.

Water was found to be effective for many highly soluble odorants. Sodium carbonate was no more effective than water, and sodium hydroxide was little better. Strong oxidizing agents were the most effective. Sodium hypochlorite was effective against a spectrum of odorants. Potassium permanganate reacted slower but attacked some odorants not handled by hypochlorite. Hydrogen peroxide was almost as effective as was sodium persulfate. Sodium bisulfite was effective only against aldehydes.

It was suggested that a 2-stage scrubber might remove a wider range of odorants than 1 stage. Two oxidizing agents might be the most effective combination, although other combinations could be tried. Tests on combinations should be done with the normal odorous emissions in a rendering plant.

2. DESIGN AND COST OF DIRECT-FIRED INCINERATORS

A design procedure for incineration by direct flame has been completed and is presented in this section.

The design method has been programmed on a time-sharing computer.

2.1 Nomenclature

Y	Concentration of odorants, moles/liter or consistent units
Y_e	Concentration of odorants in effluent stream, moles/liter
C_E	Cost of electricity, \$/KWH
C_G	Cost of fuel gas, \$/scf
C_m	Cost of maintenance, \$/cfm-year
E_F	Efficiency of fan, dimensionless
k	Reaction rate constant, sec^{-1}
H_V	Heating value, BTU/scf fuel gas
T_o	Inlet temperature of polluted air stream, °R
T_i	Inlet temperature of fuel-combustion air stream, °R
T_e	Operating temperature of incinerator, °R
t_R	Residence time in reactor, sec
Q_A	Flow rate of polluted air stream, cfm
Q_C	Flow rate of combustion products, cfm
Q_F	Flow rate of fuel gas, cfm
Q_G	Total flow rate through incinerator, cfm
V	Volume of incinerator, ft^3
W	Weight rate of plant air flow, lb/hr.

2.2 Design Equation

The reaction can be considered first order with respect to the pollutant in the plant air stream and first-order with respect to oxygen. If an excess of oxygen is present, as occurs with the incinerator shown in Figure 1, the oxygen variation will be small enough to consider it constant.

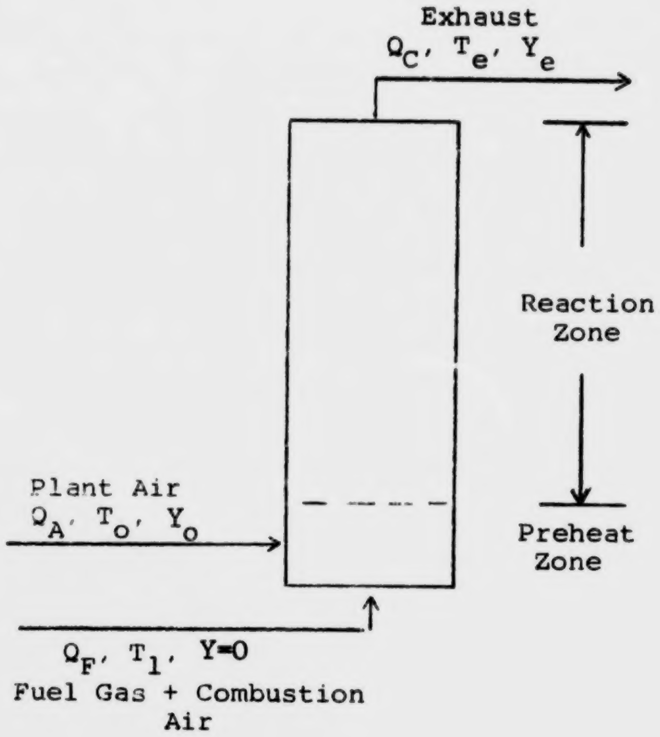

Figure 1

ODORANT INCINERATOR

For first-order kinetics and a constant volume reactor[2]

$$\ln Y_o'/Y_e = k\ t_R$$

or (1)

$$k = \ln (Y_o'/Y_e)/t_R \quad \sec^{-1}$$

where

Y_o' is the inlet concentration of pollutant
Y_e is the exit concentration of pollutant
t_R is the residence time of the pollutant.

The source of combustion air is plant air. If outside air is used, the added volume significantly increases the cost of operation. The products of flame combustion are mixed with the remaining plant air to result in the calculated temperature necessary to incinerate the odor. Therefore $Y_o' = Y_o$.

The constants A and ΔE in the Arrhenius equation were not previously known for the reaction of rendering odorants in combustion products. Preliminary estimates were made from data on the incineration of phenolic and hydrocarbon compounds produced in the enameling of wire.[5] Gas analysis was done by chromatography to determine the reduction ratios.

By expressing the Arrhenius equation as

$$\ln k = \ln A - \frac{1.8\ \Delta E}{RT} \qquad (2)$$

it was solved to give

$A = 299$
$\Delta E = 7780.$

Data was provided by one rendering company on the lowering of odor units by an incinerator (Ref. F9, see appendix page 139). The use of this data indicates a reaction rate twice as fast and a slightly different temperature coefficient. This change decreases the size of reactor required. The resulting coefficients are

$\Delta E = 9560$
$A = 1900$

These data should be checked by additional measurements on plant incinerators. They are the best values available and they were used as the basis of design calculations.

There are 2 independent variables in the incinerator design that determine the extent of oxidation of pollutants: the reactor volume and the mean gas temperature. A separate design calculation was done for each of several reactor volumes and the design having minimum cost was picked. For each chosen reactor volume there is a temperature which will give the desired reduction of odorant concentration. This temperature is determined by substituting the desired reduction ratio and the contact time corresponding to the reactor volume into the Arrhenius equation which gives the effect of temperature on the reaction rate.[2]

$$T_e = 1.8\ \Delta E/(R\ \ln(A/k)) \qquad (3)$$

where

k is determined by substituting the reduction ratio Y_o/Y_e in Eq. (1)
T_e is reactor temperature, °R
A is the Arrhenius frequency factor, 1/sec
ΔE is the energy of activation, cal/g-mole
R is the gas constant, 1.987 cal/g-mole.

2.3 Heat Input

The next problem is to determine the quantity of fuel needed to heat the plant air to the calculated reaction temperature. In the diagram of the incinerator, Figure 2 (page 13) we see that the fuel is mixed with sufficient combustion air and burned in a gas burner. The products of combustion are then mixed with plant effluent air, so that the mixture has the desired reaction temperature. A suitably designed incinerator will provide adequate mixing and the necessary retention time for reaction after mixing has been completed.

The calculation of heat requirement can be separated into 2 parts: a flame calculation and a heat balance on the mixing process. The heat balance requires us to integrate the heat capacities of 2 mixed streams: the plant air stream and the products of combustion stream.

2.4 Calculations of Heat Capacities

The heat capacity data[1] is expressed by an equation of the form

$$Cp = a + bT + C/T^2 \quad \frac{\text{cal}}{\text{g-mole °C}} = \frac{\text{BTU}}{\text{lb-mole °R}} \qquad (4)$$

where a, b and c are constants for each compound. Values are given in Table 1.

For a mixture, the heat capacity is the sum of the contributions of major components on a mole fraction basis.

$$Cp_{air} = .79\ Cp_{N_2} + .21\ Cp_{O_2}$$

Using this equation and the data from Table 1:

$$Cp_{air} = .79(6.66 + .00102\ T)$$

$$+ .21(7.16 + .001\ T - 40{,}000/T^2)$$

$$Cp_{air} = 6.78 + .00102\ T - \frac{8410}{T^2}\ .$$

Similarly the heat capacity of the methane combustion products is obtained from Tables 1 and 2.

$$Cp' = 7.124 + .00142\ T - \frac{17870}{T^2}$$

2.5 Heat Requirement

The net heat required per pound of plant air is[1]

$$H_{air} = \int_{T_o}^{T_e} Cp(air)\ dT \quad \text{BTU/lb} \qquad (5)$$

Table 1

HEAT CAPACITY COEFFICIENTS
FOR COMBUSTION PRODUCTS
Reference 1

Component	a	$b \times 10^3$	$c \times 10^{-5}$
CO_2	10.55	2.16	-2.04
H_2O	7.17	2.56	.08
N_2	6.66	1.02	-
O_2	7.16	1.0	-0.4

Table 2

COMPOSITION OF COMBUSTION PRODUCTS OF METHANE WITH THEORETICAL AMOUNT OF AIR

Reference 2

Component	ft^3/ft^3	Mole %
CO_2	1.00	9.5
H_2O	2.00	19.0
N_2	7.52	71.5
	10.52	100.00

Heating Value of Natural Gas = 1011 BTU/scf at 60°F

where

ΔH is the heat requirement, BTU/lb

Cp is the weighted average heat capacity of the major constituents of the air stream, BTU/lb-mol °R

T_o and T_e are inlet and outlet temperature, °R.

Integrating and using heat capacity data from the previous page

$$\Delta H_{air} = [6.78(T_e-T_o) + .000509(T_e^2-T_o^2) - 8410(T_e-T_o)/T_e-T_o]/28.8 \qquad (6)$$

where

28.8 is the molecular weight of air.

2.6 Net Heating Value

The net heat available from one standard cubic foot of the fuel gas[1] is

$$\text{Net Heat} = H_V - \int_{T_1}^{T_e} Cp'\, dT/F_c \quad \text{BTU/scf of fuel gas} \qquad (7)$$

where

H_V is the gross heating value of the fuel gas with the products of combustion at 60°F

Cp' is the weighted average of the major constituents of the combustion products of the fuel gas, BTU/lb mole °R

T_1 and T_e are inlet and exit temperatures, °R

F_c = conversion factor = 379/10.52 = 36.1

10.52 = moles combustion products/mole fuel gas

379 = scfm fuel gas/lb-mole fuel gas

Integrating and using data from References 1 and 2

$$H_N = \text{Net Heat} = 1011 - [7.124(T_e - T_1) + .00071(T_e^2 - T_1^2) - 17870(T_e - T_1)/T_e - T_1]/36.1 \quad \text{BTU/scfm fuel gas.} \qquad (8)$$

2.7 Fuel Requirements

The total fuel requirement is given by

$$Q_g = \text{Fuel} = \Delta H_{air}\, W_{air}\, 1.1(1 - F_H)/H_N \quad \text{scf/min} \qquad (9)$$

where

ΔH_{air} is the heat requirement, BTU/lb

W_{air} is the flow rate of the air stream, lb/min

H_N is the net heating value, BTU/scf

1.1 is a factor to correct for an assumed 10% heat loss through the incinerator walls

F_H is the fraction of sensible heat that is recovered by means of a heat exchanger.

Equations to design this exchanger have not not been included. Preliminary estimates indicated that the savings in fuel are balanced by the added investment cost.

2.8 Volume of Combustion Products

$$Q_C = 10.52\ Q_F \frac{T_e}{510} \tag{10}$$

where

Q_F is the volumetric flow rate of the fuel gas, cfm

T_e is the reactor temperature, °R

The factor 10.52 is a mol ratio deduced from the stoichiometry of methane combustion from Table 8.

2.9 Equation to Compute Fraction of Air Used for Combustion

Part of the plant air is used as combustion air in the gas burner, and the rest is mixed with the combustion products. The flow scheme is shown in Figure 2.

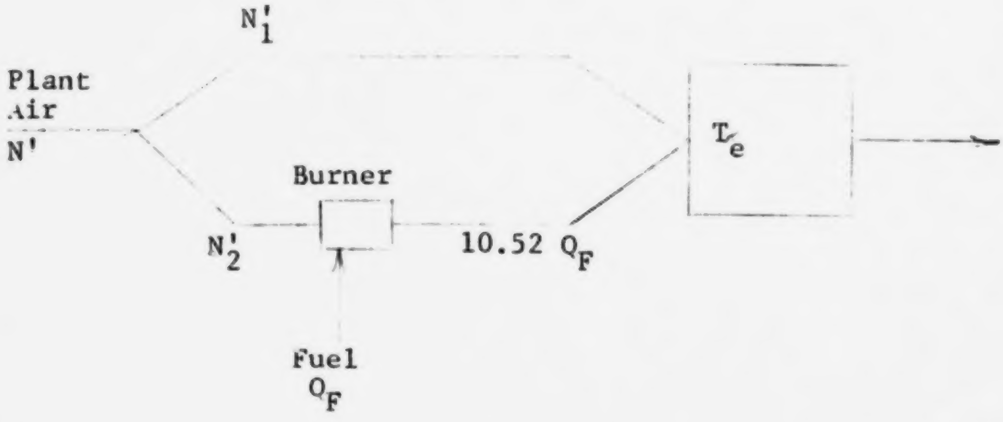

Figure 2

ODORANT INCINERATOR USING PLANT AIR FOR COMBUSTION

The material balance is on a mol basis, where N' represents the number of moles of each stream.

$$N_2' = \text{air flow} = 9.52\ Q_F \text{ (by stoichiometry of combustion)} \qquad (11)$$

$$9.52 \text{ air} = 2\ O_2 + 7.52\ N_2 + CH_4 \rightarrow 7.52\ N_2 + CO_2 + 2H_2O$$

By material balance on air

$$N' = N_1' + N_2' = N_1' + 9.52\ Q_F$$

$$Q_F = \frac{N'-N_1'}{9.52} \qquad (12)$$

By heat balance on system

$$N_1' \int_{T_1}^{T_e} Cp_1 dt + 10.52\ Q_F \int_{T_o}^{T_e} Cp_2 dt = H_V\ Q_F \qquad (13)$$

$$N_1' \int_{T_1}^{T_e} Cp_1 dt = [H_V - 10.52 \int_{T_o}^{T_e} Cp_2 dt] Q_F \qquad (14)$$

$$\frac{N_1'}{Q_F} = \frac{H_V - 10.52 \int_{T_o}^{T_e} Cp_2 dt}{\int_{T_1}^{T_e} Cp_1 dt} = R = \text{ratio} \qquad (15)$$

From Eq. 12

$$\frac{N_1'}{\frac{N'-N'_1}{9.52}} = \frac{9.52\ N_1'}{N'-N_1'} = R$$

$$N_1'(9.52 + R) = N'R$$

$$\frac{N_1'}{N'} = \frac{R}{9.52 + R}$$

$$\text{Fraction} = \frac{N_2'}{N'} = \frac{12.5\ N_{ETHT}/H_{Air}}{9.52 + 12.5\ N_{ETHT}/H_{Air}} \quad \cdots\cdots \quad (16)$$

2.10 Reactor Volume[2]

This volume is based on the actual flow rate and the assumed residence time.

$$\text{Volume} = \frac{(Q_A + Q_C)t_R}{60} \qquad (17)$$

where

Q_A and Q_C are the flow rates of the air stream and the combustion product stream, ft^3/min

t_R is residence time, sec

The design calculations must be repeated for several residence times.

2.11 Pressure Drop

The entire gas pressure drop can be considered to be in the duct and in the entrance to the incinerator. By proper sizing of ducts, the pressure drop can be kept to one inch of water. From IITRI Report No. C8210-3:

$$P_w = 1.57 \times 10^{-4}\ \Delta P\ Q_A/E_F \quad \text{Hp} \qquad (18)$$

where

ΔP is pressure drop, in. of water

Q_A is plant air throughput, cfm

E_F is fan efficiency, dimensionless.

2.12 Initial Cost

Having computed the reactor volume, we can now compute the equipment cost. The installed cost of an incinerator is expressed in terms of its volume. It can be estimated from a correlation of data found in IITRI Report No. C8210-3, page 25.

$$\text{Installed cost} = 7300\ V^{0.34} \tag{19}$$

where

V is volume of the incinerator, cu ft.

This is the effective volume of the gas in the incinerator at the incineration temperature. It does not include the volume of the combustion zone.

2.13 Operating Cost

The operating cost includes fuel, fan power and maintenance costs.

2.14 Annual Fuel Gas Cost

$$\text{Cost} = \theta\ C_G\ Q_g\ 60/1000 \tag{20}$$

where

θ is the number of hours of operation per year

C_G is the cost of fuel gas, \$/MCF

Q_g is the rate of fuel consumption, scfm.

2.15 Power Cost

$$\text{Cost} = .746\ \theta\ P_w C_E \tag{21}$$

where

θ is the number of hours of operation per year

P_w is the power required from the fan from Eq. 9, KW

C_E is the cost of electricity, \$/KWH.

2.16 Maintenance Cost

The annual maintenance cost is[4]

$$\text{Cost} = C_m Q_G \tag{22}$$

$$= 0.06\ Q_G$$

2.17 Total Operating Cost

$$\text{Cost} = Q_G(1.17 \times 10^{-4}\ \theta\ \Delta P\ C_E/E_F + C_m) + 0.06\ \theta\ C_G Q_F \tag{23}$$

2.18 Economic Evaluation

The summary of costs is given in Table 3. These data are summarized from computer results for costs at various reactor temperatures and represent the optimum reactor temperature with regard to total annual cost. The fuel costs are comparable to those estimated by others, except for a 10% allowance for heat loss for the reactor. Probably, this allowance should be neglected for large systems.

2.19 References

1. Metallurgical Thermochemistry, Kubaschewski and Evans, Pergamon Press, 1958, pp. 310-25 (Table of Cp data).

2. Engineering Manual, Second Ed., Robert E. Perry, Ed., McGraw Hill, 1967, Sec. 5, pp 63ff and Sec. 8, pp 72.

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4. Control Techniques for Particulate Air Pollution, Report of U. S. Dept. of HEW, Public Health Service, Consumer Protection and Environmental Health Service, 1969, pp 6-50, 53.

5. Benforada, D. M. and Waitkus, Joseph, Fume Control in Wire Enameling by Direct Flame Incineration, J. Air Poll. Control Assn., 18(1), 24-6, 1968.

Table 3

INCINERATOR COST SUMMARY

		Reactor			Costs			
Flow, CFM	Reduction Ratio Odor Concentration	Temp., °F	Residence Time, sec	Volume, cu ft	Investment, $	Fuel* $/Year	Total $/Year	$/1000 CFM-Hr
1,000	100	1069	.7	33	12,500	3,150	6,400	1.28
	1,000	1186	.7	36	13,000	3,570	6,950	1.39
	100,000	1236	1.0	52	15,200	3,753	7,703	1.55
5,000	100	1069	.7	164	24,500	15,700	22,540	.90
	1,000	1082	1.0	237	28,500	16,000	23,800	.95
	100,000	1111	1.5	362	34,000	16,500	25,700	1.03
25,000	100	1069	.7	885	49,500	87,000	103,000	.83
	1,000	1082	1.0	1276	57,600	88,500	106,500	.85
	100,000	1111	1.5	1952	68,800	91,300	112,300	.90

*Based on 5,000 hours operation per year.

3. CATALYTIC BED AFTERBURNER DESIGN EQUATIONS

Design equations for a catalytic afterburner are presented. A computer program was written with these equations and several examples are given.

Since a direct flame incinerator has a relatively high cost due to the high operating temperatures, use of a catalyst to reduce the incineration energy requirement offers a potential advantage. A catalyst is a material which promotes chemical reaction, although it does not enter into the reaction.

The catalyst will cause a faster rate of reaction at relatively low temperatures than can be achieved in a direct fired incinerator. It allows incineration at a lower temperature.

Catalysts are normally porous particles and are frequently used in a fixed bed contactor. The design of a catalyst bed reactor depends in part on diffusion through these pores. For certain types of catalyst in which the pore passages are short, pore diffusion can be neglected. In this case the controlling factor is mass transfer to the gross surface of the catalyst. The present results are limited to this type of catalyst.

3.1 Nomenclature for Catalytic Reactor Design

a	Specific surface area of catalysts, sq ft/cu ft
A_m	Amortization factor, 1/yr
C_{ANN}	Annual cost of catalytic afterburner, \$/yr
C_{cat}	Cost of catalyst, \$/cu ft
C_{TC}	Cost of catalyst bed, \$
C_D	Cost of ducting, \$/ft
C_E	Cost of electricity, \$/KWH
C_{TE}	Cost of electricity, \$/yr
C_T	Capital cost of catalytic afterburner, \$
C_F	Cost of fan, \$/cu ft

C_{TF}	Cost of fan, $
C_{Fu}	Cost of fuel gas, $/MCF
C_{TFu}	Cost of fuel, $/yr
C_H	Cost of housing for catalyst bed, $
C_I	Cost of insulation for catalyst housing, $/ft
C_M	Cost of maintenance, $/cu ft
C_{TM}	Cost of maintenance, $/yr
d	Diameter of tube, in.
E_F	Fan efficiency, dimensionless
G_M	Molar flow rate, lb moles/hr-sq ft
Hp	Horsepower needeeded for fan, Hp
j_o	Colburn j factor, dimensionless
k_g	Mass transfer coefficient, lb/hr-sq ft-atm
N	Number of modules, dimensionless
N_F	Exponent on flow in fan cost equation
P	Total pressure, atm
P_{BM}	Log mean pressure of non-diffusing gas, atm
Q_A	Flow rate of odorous air stream entering preheater, cu ft/min
Q_{AF}	Flow rate of odorous air stream leaving preheater, cu ft/min
Q_C	Flow rate of combustion products leaving preheater, cu ft/min
Q_F	Flow rate of fuel gas, scfm
Q_T	Flow rate entering catalyst bed, cu ft/min
Re	Reynolds number, dimensionless
Sc	Schmidt number, dimensionless
T_o	Inlet temperature of odorous air stream, °F
T_1	Inlet temperature of fuel gas stream
T_E	Outlet temperature of combined air stream
Y_o	Mole fraction of odorant in odorous air stream
Y_e	Mole fraction of odorant in effluent air stream

Y_2	Mole fraction of odorant entering catalyst bed
Z	Length of catalytic reactors, ft
ΔP	Total pressure drop through catalytic bed, in. of H_2O

3.2 Design of Preheater

It is necessary to preheat the raw plant effluent gases to a temperature of approximately 800°F before they are treated by the catalytic unit. This can be done by a direct flame preheater. The flow arrangement is shown in Figure 3.

The design method and computer program for the preheater are the same as those used for the direct fired incinerator.

The volumetric flow rate into the catalytic unit is now

$$Q_T = Q_A \frac{T_1 + 460}{T_o + 460} + 10.52\, Q_F \frac{T_1 + 460}{60 + 460}$$

where 10.52 is the ratio of volume of combustion products at 60°F to the volume of fuel gas consumed, and the temperature ratios are based on the ideal gas law.

For some odorants, there will be a significant amount of reaction from the direct flame preheater. The amount of reaction will depend upon the residence time prior to entering the catalytic section of the reactor and the temperature used. This will be computed from the equations used in the design of a direct flame incinerator.

3.3 Catalytic Afterburner Design Longitudinal Flow

3.3.1 Design Equation for Honeycomb Catalyst

A material balance around a differential element for a fixed bed catalytic reactor with mass transfer controlling gives

$$-G_m dy = k_g a\, PY\, dZ \tag{24}$$

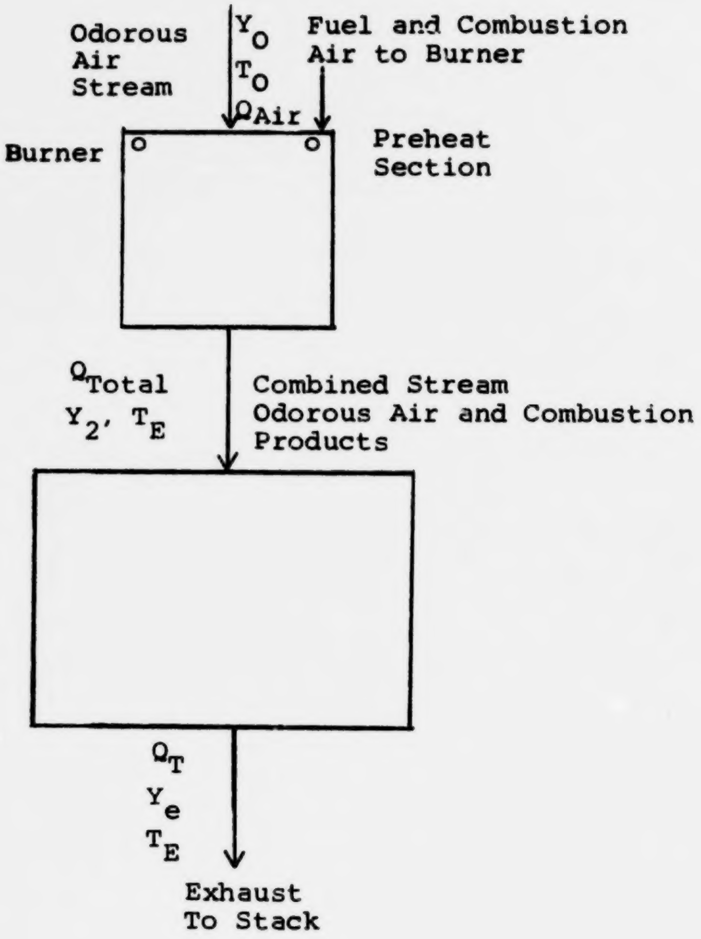

Figure 3

PREHEATER AND CATALYTIC AFTERBURNER

where

G_m is the molar flow rate, lb moles per sq ft hr
Y is the mole fraction of odorant
k_g is the mass transfer coefficient, lb moles per sq ft hr atm
a is the area for mass transfer, sq ft per cu ft or sq in/cu in
P_T is the total pressure, atm
Z is the length of the reactor, ft.

Integrating from $(Y = Y_o,\ Z = 0)$ to $(Y = Y_e,\ Z = Z)$

$$\ln \frac{Y_2}{Y_e} = \frac{k_g a}{G_m} \quad P_T Z \tag{25}$$

Consider a reactor using a honeycomb type of catalyst support with flow in the longitudinal direction. The honeycomb catalyst support can be obtained in one-foot square units of short lengths. They may be stacked to any desired depth.

It is convenient to design for modules of one square foot and of suitable length. The number of modules is determined by a trial-and-error calculation to result in a reasonable pressure drop. Since the number is dependent on the total flow, an initial value is

$$N = Q_{AF}/1500$$

where Q_{AF} is the flow rate of odorous air at temperature T_E. The flow through the honeycomb passages can be treated like flow in a pipe. In this case for $4000 < Re < 6000$; $6 < Sc < 3000$, mass transfer is correlated[1] by

$$j_0 = \frac{k_g P_{BM}}{G_M} \ Sc^{2/3} = .023\ (Re)^{-.17} \tag{26}$$

where

P_{BM} is the log mean pressure of the non-diffusing gas. For dilute mixtures of contaminants this is approximately the total pressure, P_T.

G_M is the molar flow rate, lb moles per sq ft-hr

k_g is the mass transfer coefficient, lb moles per sq ft - hr atm

Sc is the Schmidt number

$$Sc = \text{Viscosity } \left(\frac{\text{lb}}{\text{ft-hr}}\right) / \left[\text{density } \left(\frac{\text{lb}}{\text{cu ft}}\right) \text{ diffusivity } (\text{ft}^2/\text{hr})\right]$$

Re is the Reynolds number

$$Re = \frac{\text{Diameter of tube (ft) velocity (ft/hr) density (lb/cu ft)}}{\text{Viscosity (lb/ft-hr)}}$$

Substituting $\frac{k_g P}{G_M}$ from (26) into the material balance Equation (25) becomes

$$\ln \frac{Y_2}{Y_e} = \frac{.023}{(Re)^{.17} (Sc)^{2/3}} z\ a \tag{27}$$

To evaluate this a must be known

$$a = \frac{\text{Surface Area}}{\text{Unit Volume}} = \frac{\pi d z}{\frac{\pi}{4} d^2 z} = 4/d \tag{28}$$

Using this in Equation (27)

$$\ln \frac{Y_2}{Y_e} = \frac{.092\ z}{d\ (Re)^{.17} (Sc)^{2/3}} \tag{29}$$

z = length of catalytic bed, in.
d = diameter of tubular catalyst honeycomb, in.

This is the final design equation for the catalyst bed.

3.3.2 Pressure Drop Through Honeycomb Catalyst Bed

The pressure drop through the 1/8 in. Hex-cell honeycomb ceramic bed can be computed using an equation[1]

$$\Delta P = .0585\ Z\ (Q_T/144\ N)^{1.68}$$

where

Q_T is the total air flow, cfm
ΔP is the pressure drop through the bed, in. water
Z is length of catalytic bed, ft

The fan horsepower required is computed from

$$Hp = Q_T\ \Delta P/6356\ E_F$$

where

E_F is the efficiency of the fan.

3.4 Cost Calculations for a Catalytic Afterburner

3.4.1 Capital Costs

Since the shape of the honeycomb catalyst is usually a square plate, the housing will be a square duct. The cost of a housing for the catalyst bed will be determined by the cost of ducting plus the cost of insulation.

$$C_H = (C_D + C_I)\ Z\ N$$

where

C_D is the installed cost of ducting, \$ per ft
C_I is the cost of insulation, \$ per ft
Z is the required length, ft
N is the number of catalyst units required.

The cost of the catalyst is

$$C_{TC} = N\ C_{cat}\ Z\ C_{in}$$

where

C_{cat} is the cost of the catalyst, \$per cu ft
N is the number of 1 sq ft units required
C_{in} is factor for installation cost = 1.5

A typical catalyst price is $450/cu ft of bed required.[3]

A fan and motor will be required for the operation of a catalyst bed. The cost of this fan will be

$$C_{TF} = C_F \, Q_T^{N_F} + C_{MS} \, Hp$$

where

C_F and N_F are constants for the type of fan chosen
C_{MS} is the unit cost of the motor, \$ per Hp
Hp is the horsepower required
Q_T is the total flow rate through the bed.

The total capital cost is the sum of the above

$$C_T = C_H + C_{TC} + C_{TF} + C_{preheater}$$

3.4.2 Operating Costs for Catalytic Afterburner

The cost of electricity for the process is

$$C_{TE} = .746 \, C_E \, \theta \, Hp$$

where

C_E is the unit cost of electricity
θ is the number of hr per yr and Hp is the horsepower required for the fan.

The cost of maintenance is

$$C_{TM} = C_M \, Q_T$$

where

C_M is the cost of maintenance, \$ per cfm
Q_T is actual flow rate through the bed, cfm.

The cost of fuel is given by

$$C_{TFu} = Q_F \; C_{Fu}$$

where

Q_F is the flow rate of fuel, scfm

C_{Fu} is the cost of fuel, \$ per scfm.

The total annual cost is the sum of the operating costs plus the amortization

$$C_{ANN} = C_T \; A_m + C_{TF} + C_{TE} + C_{TM}$$

3.5 Design and Cost Estimate

Design and cost calculations have been carried out for a catalytic incinerator system. Results are given for three different flow rates and four different reduction ratios in Table 4. By use of a catalyst bed, the temperature necessary for incineration of odor vapors can be reduced from 1200 to about 800°F, thus reducing the fuel cost. At the same time, there is an added investment cost for the catalyst bed and additional fan cost due to pressure drop through the bed. The calculations showed that these costs are about equal to the savings in fuel costs, so that catalytic incineration offers little advantage over direct-fired incineration. Slight improvement could be obtained by finding catalysts with less pressure drop, or which operate reliably at lower temperature. However, it is clear that these improvements will be only marginal.

Only if the plant effluent gas going to the incinerator is already partly heated will a catalytic incinerator show an economic advantage, because the increment of heat necessary to reach the catalyst temperature is much less than that required to reach a direct-fired incinerator temperature. The gaseous effluent from rendering plants is not expected to exceed 120 to 140°F, and this temperature is not sufficient to affect the heat economy. If a condenser is used, as may be necessary to scrub

Table 4

CATALYTIC INCINERATION DESIGN AND COST ESTIMATES

```
 TEMPERATURE    DEGREES F
  INLET    OUTLET
       32.          800.

          UNIT COSTS OF CAPITAL EQUIPMENT
 CATALYST     DUCTING     INSULATION           BLOWER
      650.      15.00        10.   COEFFICIENT 11.00   EXPONENT .680

                 UNIT COSTS OF OPERATION
 FUEL GAS      POWER     MAINTENANCE     AMORTIZATION      ANNUAL HOURS
  $/MCF        $/KWH      $/CFM-YR          FACTOR         IN OPERATION
  .500         .015        .080              .250               5000.
.0312698412698841 .0790288414991191


      CALCULATED OPERATING CONDITIONS
 SPACE VEL.     REYNOLDS NO.     SCHMIDT NO.      PRESSURE DROP     HORSEPOWER     NUMBER OF UNITS
   1/HR                                           IN. OF WATER
  72013.            589          2.529              28.12           105.43                   5.

 FLOW RATE    ODORANT CONCENTRATION        LENGTH      CAPITAL COST       ANNUAL OPERATING COST      TOTAL OPERATING COST
   CFM           INLET     OUTLET           FEET    INSTALLED   ANNUAL    FUEL    POWER   MAINT      ANNUAL   $/1000CFM-HR
   1000.          10.         1.            .636      10053.    2513.   2712.     203.   210.       5637.          1.13
   1000.         100.         1.           1.402      10721.    2680.   2712.     447.   210.       6048.          1.21
   1000.        1000.         1.           2.169      11388.    2847.   2712.     691.   210.       6459.          1.29
   1000.      100000.         1.           3.702      12723.    3181.   2712.    1180.   210.       7282.          1.46


     CALCULATED OPERATING CONDITIONS
 SPACE VEL.     REYNOLDS NO.     SCHMIDT NO.      PRESSURE DROP     HORSEPOWER     NUMBER OF UNITS
   1/HR                                           IN. OF WATER
  72013.            589          2.529              28.12           527.15                  25.

 FLOW RATE    ODORANT CONCENTRATION        LENGTH      CAPITAL COST       ANNUAL OPERATING COST      TOTAL OPERATING COST
   CFM           INLET     OUTLET           FEET    INSTALLED   ANNUAL    FUEL    POWER   MAINT      ANNUAL   $/1000CFM-HR
   5000.          10.         1.            .636      23770.    5943.  13558.    1013.  1049.      21562.           .86
   5000.         100.         1.           1.402      27108.    6777.  13558.    2234.  1049.      23618.           .94
   5000.        1000.         1.           2.169      30446.    7612.  13558.    3456.  1049.      25674.          1.03
   5000.      100000.         1.           3.702      37123.    9281.  13558.    5899.  1049.      29786.          1.19


      CALCULATED OPERATING CONDITIONS
 SPACE VEL.     REYNOLDS NO.     SCHMIDT NO.      PRESSURE DROP     HORSEPOWER     NUMBER OF UNITS
   1/HR                                           IN. OF WATER
  72013.            589          2.529              28.12           527.15                  25.

 FLOW RATE    ODORANT CONCENTRATION        LENGTH      CAPITAL COST       ANNUAL OPERATING COST      TOTAL OPERATING COST
   CFM           INLET     OUTLET           FEET    INSTALLED   ANNUAL    FUEL    POWER   MAINT      ANNUAL   $/1000CFM-HR
  25000.          10.         1.            .636      62128.   15532.  67789.    5064.  5243.      93628.           .75
  25000.         100.         1.           1.402      78818.   19705.  67789.   11172.  5243.     103909.           .83
  25000.        1000.         1.           2.169      95509.   23877.  67789.   17279.  5243.     114189.           .91
  25000.      100000.         1.           3.702     128889.   32222.  67789.   29494.  5243.     134749.          1.08
```

out fatty particles that may interfere with the catalyst, then the temperature will be even lower. We conclude that catalytic incineration is not promising for this application.

3.6 References

1. Mass Transfer Operations (sec Ed.), Robert E. Treybal, McGraw Hill, 1955, pages 60-67.
2. A Study of Catalyst Support Systems for Fume-Abatement of Hydrocarbon Solvents, M. R. Miller and H. J. Wilhoyte, Journal of the Air Pollution Control Association, Vol. 17 (12).
3. Private Communication, Don Bissel, Ispen Ceramics Inc., Pecatonica, Illinois, Jan. 1972.

4. CARBON BED ADSORPTION

The economics of carbon bed adsorption is different from the other methods considered, and it may have a place in certain applications. The cost of the carbon and of its regeneration depend strongly on the odorant concentration to be removed, so that carbon can be considered for treatment of very dilute odors, such as ventilation air. Design computer programs have not been developed but a rough example calculation is given below.

4.1 Design Based on Equilibrium Capacity

The example is to treat 100,000 cfm of ventilation air containing only 10 ppm of odorant. It is assumed that a 100-fold reduction in concentration is sufficient for ventilation air, although much greater reductions are needed for process air. The amount of carbon needed is calculated from equilibrium based on the capacity of the carbon. Data is available from Calgon Corp. on the capacity of carbon for isopropyl alcohol. Odorous materials of higher molecular weight and less polarity will be more readily adsorbed, and therefore this is a safe method of design. Figure 4 is an adsorption isotherm for isopropyl alcohol on carbon at 77°F. It gives the capacity of the carbon depending on the concentration of isopropyl alcohol in the air being treated.

10 ppm corresponds to 0.0076 mm Hg vapor pressure of isopropyl alcohol. At this pressure the bed capacity is 3.8 lb/100 lb carbon. A cubic foot of carbon weighs 20 lb, so this is 0.7 lb/cu ft of bed. The total quantity of odorant removed depends on the flow rate and the concentration. 10 ppm corresponds to

$$\frac{10 \times 10^{-6}\ \text{ft}^3 \quad 60.1\ \text{lb} \quad 1000}{\text{ft}^3 \quad 392\ \text{ft}^3 \quad 1000} = \frac{.0015\ \text{lb isopropanol}}{1000\ \text{ft}^3\ \text{air}} \qquad (30)$$

This uses up $\frac{.0015 \times 100}{.7} = \frac{.216\ \text{ft}^3\ \text{bed}}{\text{min}}$ for an air flow of 100,000 cfm. For a 16-hr day this requires a 208 ft^3 bed.

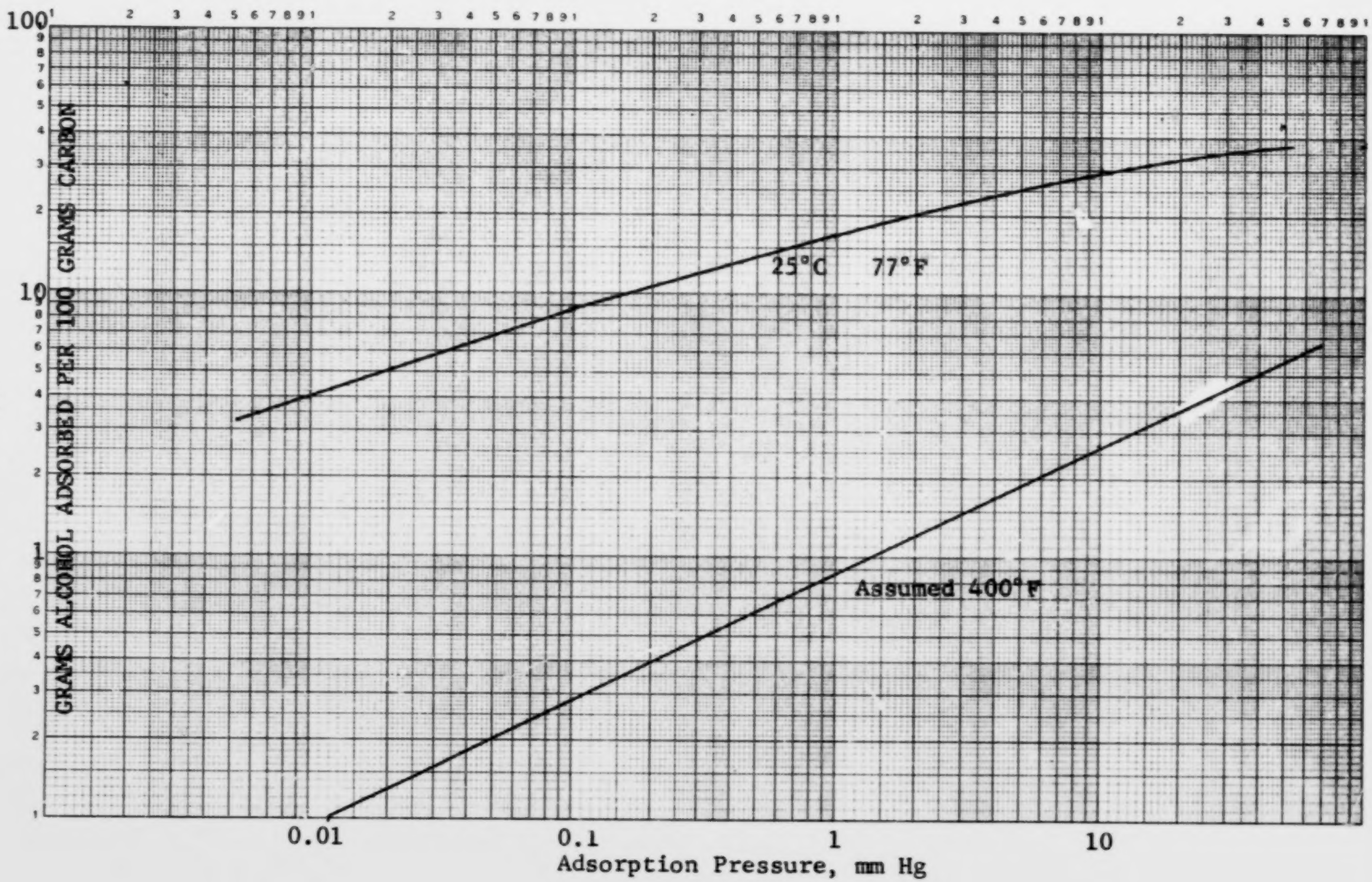

Figure 4

ESTIMATED ADSORPTION OF ISO PROPYL ALCOHOL ON BPL CARBON
Courtesy Calgon Corp.

4.2 Pressure Drop

The second major cost of carbon bed treatment is the cost of forcing the air through the bed. This depends on the thickness of the bed. If the bed is made too thin, mass transfer rate might limit the adsorption process. However, mass transfer data on packed beds (Ref. E-10) indicate that a bed 10 particles thick will remove several orders of magnitude of odorant concentration. Therefore, a design of bed is chosen spreading the 208 ft^3 over an area to give a bed thickness of 1 in. and the bed area is 2496 sq ft. The air velocity is 40 ft/min. From Figure 5 the pressure drop for a 6-16 mesh carbon bed is 4 in. water pressure. The power required is (from Report C8210-9, p. 26)

$$Hp = \frac{Q_T \; \Delta P}{6356 \; E_F} = \frac{100,000 \times 4}{6356 \times .7} = 90 \text{ hp} \tag{31}$$

4.3 Regeneration by Incineration

The final major cost is the cost of regeneration. The most logical way to regenerate a carbon bed is by use of hot air, since the effluent from the bed can be economically purified by a direct-fired incinerator. Part of the incinerator effluent can be mixed with fresh air and recycled to perform the regeneration. We have not worked out the details of this scheme, but previous calculations of the cost of direct-fired incineration can be used for a rough cost estimate.

The regeneration would take place at the end of the day and would require 2 hrs. If an incinerator is also used for process air treatment, then the same incinerator could be used for the regeneration air. The ability to regenerate depends on the change in adsorption isotherm for the higher gas temperature; an estimated curve is shown in Figure 4 for 400°F. Assuming a 100 to 1 concentration effect due to regenerating between 400 and 500°F, the volume of regeneration air is 1/100 the volume of air deodorized. This means that in 2 hrs a flow of 8000 cfm will regenerate the

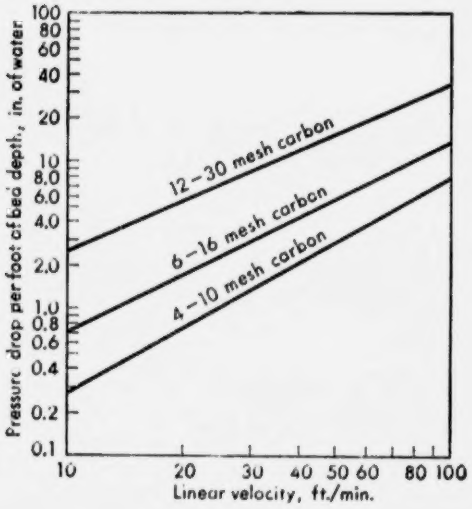

Figure 5

PRESSURE DROP THROUGH CARBON BEDS

From Yocum, J. E., and Duffee, R. A., Controlling Industrial Odors, Chem. Engr., June 15, 1970, p. 165.

bed which treated 100,000 cfm for 16 hrs. From the incinerator cost Table 3, the investment cost is about $40,000. The fuel cost is less than given in the table, because the time of operation is only 2 hrs per day. This calculation requires that the flow during regeneration be counter-current to the normal flow during use, since otherwise additional time would be required to thoroughly purge the final portion of the bed near the outlet.

4.4 Total and Annual Costs

The total and annual costs are listed in Table 5. The total cost per 1000 cfm-hr is only $.11, lower than the other methods considered. However, this is only for ventilation air. A similar calculation was done for process air, assuming 1000-fold reduction in concentration. The bed capacity and regeneration costs rise sharply.

It should be emphasized that these costs are only rough ones, and are based on data for compounds other than actual odorants. They do suggest that carbon beds can be considered for ventilation air.

Table 5

COSTS FOR CARBON BED TREATMENT OF VENTILATION AIR WITH LOW ODOR CONCENTRATION

	Total	Annual*
Carbon Bed Investment		
Carbon, 208 ft^3	\$ 3,000	
Housing	40,000	
Fan	10,000	
Ducting, installation	30,000	
Total	\$83,000	\$21,000
Incinerator Investment		
8000 cfm	40,000	10,000
Operating Costs		
Fan Power		5,000
Incinerator (Fuel)		4,000
Maintenance		15,000
Total		\$55,000
Cost per 1000 cfm-hr		\$0.11

*Based on 5,000 hours operation per year.

5. DESIGN AND COST OF COUNTER-CURRENT PACKED TOWER GAS SCRUBBING SYSTEM

A design procedure has been completed for counter-current packed scrubbing towers, and is presented in this section. A procedure for spray scrubbers is given in the next section.

This design method has been programmed on a time-sharing computer system and was used to design the experimental scrubber for use on the project. There are two versions of the program, one of which performs a series of calculations at different gas and liquid flow rates to explore the minimum cost design. The other version performs a calculation at given gas and liquid rates. Costs are expressed in terms of investment cost, as well as annual amortized and operating costs.

5.1 Nomenclature

A	cross-sectional area of towers, ft^2
a, a_{AW}	wetted surface area of packing
a_p	surface area of packing per unit volume of packing, ft^2/ft^3
C_E	cost of electricity, \$/KWH
C_F	friction factor
C_M	cost of labor and maintenance, \$/cfm
ΔP, $\Delta P'$	pressure drop, in. H_2O, ft of air
d_s	equivalent diameter of a particle packing (ft)
E_F	efficiency of fan
E_p	efficiency of pump
ϵ, ϵ_o	porosity of dry and wetted packing
G	gas rate, lb/hr ft^2
G_M	gas rate, lb mole/hr ft^2
G_T	gas throughput, lb/hr
k_Ga	overall gas phase mass transfer coefficient
L	liquid rate, lb/hr ft^2
L_M	liquid rate, lb mole/hr ft^2
L_T	liquid throughput, lb/hr
m	constant

n	constant
P	partial pressure of gas
Q_G	gas throughput, cfm
Q_L	liquid throughput, gpm
Sc	Schmidt number
v_H	correction factor for holdup
X	mole fraction of liquid
Y	mole fraction of gas
Y_E	exiting concentration of gas
Y_i	gas concentration at interface
Y_o	entering concentration of gas
Z	height of tower, ft

Greek Letters

α, β	constants
θ	operating time per year, hours
μ_G	viscosity of gas, lb/ft hr
ρ_G	gas density, lb/ft^3
ϕ_t	reduction in packing porosity due to holdup, fraction

5.2 Design Equation

Consider the packed tower shown in Figure 6.

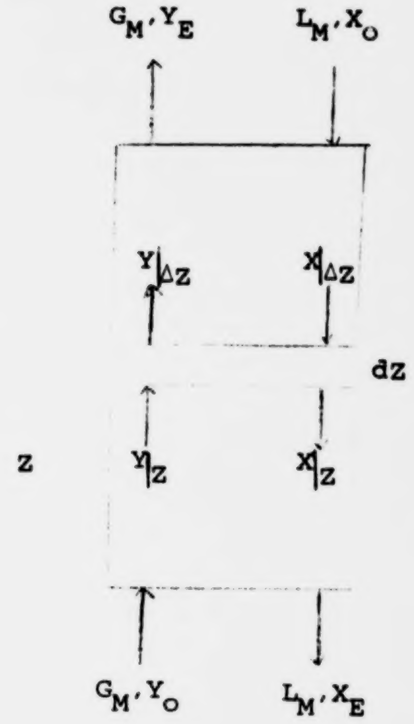

Figure 6

PACKED TOWER

If a material balance for the odorous substance is performed on an increment of volume within the tower,

$$\begin{aligned} - G_M \, A \, dY = L_M \, A \, dX &= k_G a \, (P-P_i) \, A \, dZ \\ &= k_G a \, P_T \, (Y-Y_i) \, A \, dZ \end{aligned} \tag{32}$$

where

Z	is height
G_M and L_M	are the molar gas and liquid rates per unit area
A	is the cross-sectional area
Y and X	mole fraction of pollutant in the gas phase and liquid phase
k_G	the gas phase mass transfer coefficient, a wetted specific surface area of the packing
P	is partial pressure of pollutant
P_i and Y_i	are interfacial pressure and mole fraction of pollutant
P_T	total pressure.

Integrating equation 32

$$Z = \frac{G_M}{k_G a \ P_T} \int_{Y_E}^{Y_o} \frac{dY}{Y - Y_i} \tag{33}$$

where

Y_o and Y_E are the entering and exiting mole fractions of the pollutant

For the case of a fast reaction occurring in the liquid phase, the concentration Y_i of the pollutant at the liquid surface will be approximately zero. Equation 33 then becomes

$$\begin{aligned} Z &= \frac{G_M}{k_G a \ P_T} \int_{Y_E}^{Y_o} \frac{dY}{Y} \\ &= \frac{G_M}{k_G a \ P_T} \ln \frac{Y_o}{Y_E} \end{aligned} \tag{34}$$

5.3 Correlation for Mass Transfer Coefficient

For particle packings such as rings and saddles, the gas phase mass transfer coefficient has been expressed in the form of an empirical equation. (Ref. E-6, p. 165).

$$\frac{G_M}{k_G a\ P_T} = \frac{.837}{a} \left[\frac{d_s\ G}{\mu_G (1-\epsilon_o)} \right]^{0.36} \quad Sc^{2/3} \tag{35}$$

where

$G(lb/hr\ ft^2)$	is the mass gas flow rate per unit area
ϵ_o	the operating void space
$d_s(ft)$	the diameter of a sphere of the same surface as a single packing particle
$\mu_G(lb/ft\ hr)$	gas viscosity
Sc	Schmidt number.

The wetted specific area is given by

$$a = a_{AW}\ V_H$$

where (36)

$$a_{AW} = m\ G^n\ L^p$$

$L\ (lb/hr\ ft^2)$ is the mass liquid flow rate per unit area; m, n, p are constants as given in Table 6; H is holdup correction as given in Table 7; and ϵ_o is given by

$$\epsilon_o = \epsilon - \phi_t$$

where

ϵ_o is given in Table 8

ϕ_t is given in Table 7.

5.4 Correlation for Pressure Drop

The pressure drop per foot of packing is given by (Ref. E-9)

$$\Delta P = \frac{\alpha}{\rho_G} 10^{\beta \frac{L}{3600}} \left(\frac{G}{3600}\right)^2 \tag{37}$$

Table 6

INTERFACIAL AREAS FOR ABSORPTION, DESORPTION, AQUEOUS LIQUIDS[†]

For gases of density approximating 0.075 lb/cu ft, and below loading, $a_{aw} = mG'^{n}L'^{p}$. For other gases, substitute $G'(0.075/\rho_G)^{0.5}$ for G'. (Note: The original data cover L' up to 4,500 lb/(hr)(sq ft). Extrapolation to $L' = 7,500$ has been suggested.)

Packing	Size, in.	Range of L', lb/(hr)(sq ft)	*m*	*n*	*p*
Raschig rings	0.5	500–1,500	8,200	$3.15(10^{-4})L' - 0.30$	−1.04
		1,500–4,500	9.32	$0.151(10^{-4})L' + 0.148$	−0.111
	1	500–1,500	0.274	0	0.552
		1,500–4,500	463	$0.528(10^{-4})L' - 0.0793$	−0.47
	1.5	500–1,500	1.82	$0.675(10^{-4})L' - 0.1013$	0.274
		1,500–4,500	4.85	$0.148(10^{-4})L' - 0.022$	0.140
	2	500–1,500	0.401	0	0.481
		1,500–4,500	0.95	0	0.362
Berl saddles	0.5	500–1,500	0.0336	0.0529	0.761
		1,500–4,500	2.54	0.0529	0.170
	1‡	500–1,500	15.89	$0.686(10^{-4})L' - 0.1029$	0
		1,500–4,500	238	$0.420(10^{-4})L' - 0.0630$	−0.359
	1.5‡	500–1,500	0.613	0.0508	0.455
		1,500–4,500	465	$0.325(10^{-4})L' - 0.0996$	−0.1355

† Data of Shulman et al.

‡ For $G' = 800$ lb/(hr)(sq ft) only. For higher values, see Shulman, *AIChE J.*, **1**, 253 (1955), Figs. 16 and 17.

Source: (Ref. E-6)

Table 7

LIQUID HOLDUP IN PACKED TOWERS[†]

Holdup = $\phi_t = \phi_o + \phi_s$ $\phi_{tw} = \phi_{ow} + \phi_s$ $\phi_o = \phi_{ow} H$

Packing	Nominal size, in.	d_s, ft	ϕ_s	Water (ordinary temperatures)	μ_L', centipoise	H = Correction factor for other liquids.
Ceramic Raschig rings	0.5 1 1.5 2	0.0582 0.1167 0.1740 0.238	$\frac{6.85(10^{-5})\mu_L'^{0.02}\sigma'^{0.99}}{d_s^{1.21}\rho_L^{0.37}}$	$\phi_{tw} = \frac{2.25(10^{-5})L'^{\beta}}{d_s^2}$	<12	$\frac{0.897L'^{0.57}\mu_L'^{0.13}}{\rho_L^{0.84}(0.1183L'^{0.430}-1)}\left(\frac{\sigma'}{73}\right)^{0.925-0.262\log L'}$
				$\phi_{sw} = \frac{0.00104}{d_s^{1.21}}$	>12	$\frac{0.575L'^{0.57}\mu_L'^{0.31}}{\rho_L^{0.84}(0.1183L'^{0.430}-1)}\left(\frac{\sigma'}{73}\right)^{0.925-0.262\log L'}$
				$\beta = 0.965d^{0.376}$		
Carbon Raschig rings	1 1.5 2	0.0427 0.178 0.235	$\frac{6.36(10^{-5})\mu_L'^{0.02}\sigma'^{0.23}}{d_s^{1.21}\rho_L^{0.37}}$	$\phi_{tw} = \frac{7.90(10^{-5})L'^{\beta}}{d_s^2}$	<12	$\frac{0.375L'^{0.57}\mu_L'^{0.13}}{\rho_L^{0.84}(0.174L'^{0.315}-1)}\left(\frac{\sigma'}{73}\right)^{0.925-0.262\log L'}$
				$\phi_{sw} = \frac{0.00250}{d_s^{1.21}}$	>12	$\frac{0.239L'^{0.57}\mu_L'^{0.31}}{\rho_L^{0.84}(0.174L'^{0.315}-1)}\left(\frac{\sigma'}{73}\right)^{0.925-0.262\log L'}$
				$\beta = 0.706d_s^{0.376}$		
Ceramic Berl saddles	0.5 1 1.5	0.0532 0.1050 0.155	$\frac{1.641(10^{-4})\mu_L'^{0.04}\sigma'^{0.55}}{d_s^{1.56}\rho_L^{0.37}}$	$\phi_{tw} = \frac{2.50(10^{-5})L'^{\beta}}{d_s^2}$	<20	$\frac{1.291L'^{0.57}\mu_L'^{0.13}}{\rho_L^{0.84}(0.212L'^{0.413}-1)}\left(\frac{\sigma'}{73}\right)^{1.033-0.262\log L'}$
				$\phi_{sw} = \frac{0.00032}{d_s^{1.56}}$	>20	$\frac{0.752L'^{0.57}\mu_L'^{0.31}}{\rho_L^{0.84}(0.212L'^{0.413}-1)}\left(\frac{\sigma'}{73}\right)^{1.033-0.262\log L'}$
				$\beta = 0.965d_s^{0.376}$		

† Data of Shulman et al.

Source: (Ref. E-6)

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Table 8

CHARACTERISTICS OF RANDOM PACKINGS[†]

Packing	Nominal size, in.										
	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2	3	$3\frac{1}{2}$
Raschig rings:											
Ceramic:[‡]											
C_f	1,000	750	640	380	255	160	125	95	65	37	
ϵ	0.73	0.68	0.63	0.68	0.73	0.73	0.74	0.71	0.74	0.78	
a_p	240	155	111	100	80	58	45	38	28	19	
Metal:											
$\frac{1}{32}$-in. wall:											
C_f	700		300	258	185	115					
ϵ	0.69		0.84		0.88	0.92					
a_p	236		128		83.5	62.7					
$\frac{1}{16}$-in. wall:											
C_f			340	290	230	145	110	82	57	37	
ϵ			0.73		0.78	0.85	0.87	0.90	0.92	0.95	
a_p			118		71.8	56.7	49.3	41.2	31.4	20.6	
Pall rings:											
Plastic:											
C_f				97		52		32	25		16
ϵ				0.88		0.90		0.905	0.91		
a_p				110		63.0		39	31		23.4
Metal:											
C_f				71		48		28	20		
ϵ				0.902		0.938		0.953	0.964		
a_p				131.2		66.3		48.1	36.6		
Intalox saddles, ceramic											
C_f	600		265		130	98		52	40		
ϵ	0.75		0.78		0.77	0.775		0.81	0.79		
a_p	300		190		102	78		59.5	36		
Berl saddles, ceramic:											
C_f	900		380		170	110		65	45		
ϵ	0.60		0.63		0.66	0.69		0.75	0.72		
a_p	274		142		82	76		44	32		

Tellerettes,[§] $\frac{3}{4} \times 2$ in., plastic:
High density:
$C_f = 57$
$\epsilon = 0.87$
Low density:
$C_f = 65$
$\epsilon = 0.83$

[†] Table from the United States Stoneware Company. Data are for wet dumped packing in 16- and 30-in. ID towers.

[‡] Nominal size and wall thickness, in inches, for ceramic Raschig rings are, respectively, $\frac{1}{4}$, $\frac{1}{32}$; $\frac{3}{8}$, $\frac{1}{16}$; $\frac{1}{2}$ to $\frac{3}{4}$, $\frac{3}{32}$; 1, $\frac{1}{8}$; $1\frac{1}{4}$ and $1\frac{1}{2}$, $\frac{3}{16}$; 2, $\frac{1}{4}$; 3, $\frac{3}{8}$.

[§] Teller and Ford: *Ind. Eng. Chem.*, **50**, 1201 (1958).

Source: (Ref. E-6)

where

ΔP (in H_2O) is the pressure drop

ρ_G (lb/ft^2) is gas density

α and β are constants as given in Table 9.

5.5 Costs

5.5.1 Capital Costs

The capital costs are the installed costs of the tower, fans, pumps, electrical devices, motors, and packing.

5.5.1.1 Tower

The installed cost of the tower per foot of height is given in Figure 7 as a function of diameter for several materials. Table 10 was derived from Figure 7.

5.5.1.2 Fans

The installed cost of the fans is $.10/cfm or

$$\text{cost} = .10\ Q_G$$

where

Q_G is the gas throughput in cfm.

5.5.1.3 Pumps

The installed cost of the pumps is $1.50/GPM or

$$\text{cost} = 1.50\ Q_L$$

where

Q_L is the liquid throughput in gpm.

5.5.1.4 Electrical Devices and Motors

The installed cost of electrical devices is $30 HP and that of the motors $15 HP, where HP is the required horsepower.

5.5.1.5 Packing

The costs of various packings as a function of height and diameter are given in Figures 8, 9 and 10.

Table 9

PRESSURE-DROP EQUATION FOR PARTICLE PACKING

TYPE OF PACKING	MAT'L		NOMINAL PACKING SIZE (INCHES)										
			$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{3}{8}$	$1\frac{1}{2}$	2	3
INTALOX SADDLES	CERAMIC	α			1.04		0.52	0.52			0.13	0.14	
		β			0.37		0.25	0.16			0.15	0.10	
RASCHIG RINGS	CERAMIC	α			1.96	1.31	0.82	0.53			0.31	0.23	0.18
		β			0.56	0.39	0.38	0.22			0.21	0.17	0.15
BERL SADDLES	CERAMIC	α			1.16		0.56	0.53			0.21	0.16	
		β			0.47		0.25	0.18			0.16	0.12	
PALL RINGS	PLASTIC	α						0.22		0.14		0.10	
		β						0.14		0.13		0.12	
PALL RINGS	METAL	α				0.43		0.15			0.08	0.06	
		β				0.17		0.15			0.16	0.12	
RASCHIG RINGS 1/32" WALL	METAL	α				1.20							
		β				0.28							
RASCHIG RINGS 1/16" WALL	METAL	α			1.59	1.01	0.80	0.53			0.29	0.23	
		β			0.29	0.39	0.30	0.19			0.20	0.14	

EQUATION

$$\Delta p = \alpha \times 10^{\beta L}\left(\frac{G^2}{\rho_G}\right)$$ (LIMITED TO REGION BELOW FLOODING)

Δp = PRESSURE DROP - INCHES OF H_2O/FT. OF PACKING

G = GAS MASS VELOCITY - LBS./SEC. FT.^{2}

L = LIQUID MASS VELOCITY - LBS./SEC. FT.^{2}

ρ_G = GAS DENSITY - LBS./FT.^{3}

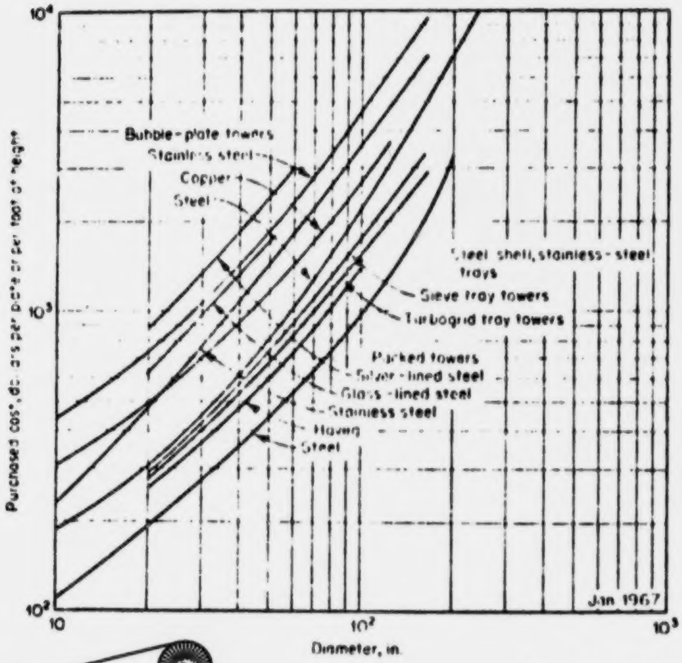
α AND β = CONSTANTS

Table 10

SCRUBBER TOWER COST PARAMETERS

$\text{Cost} = a\ D^b$

Material	Coefficient a	Exponent b
Stainless Steel	9	1.2
Steel	.133	1.92
Haveg	.016	2.48



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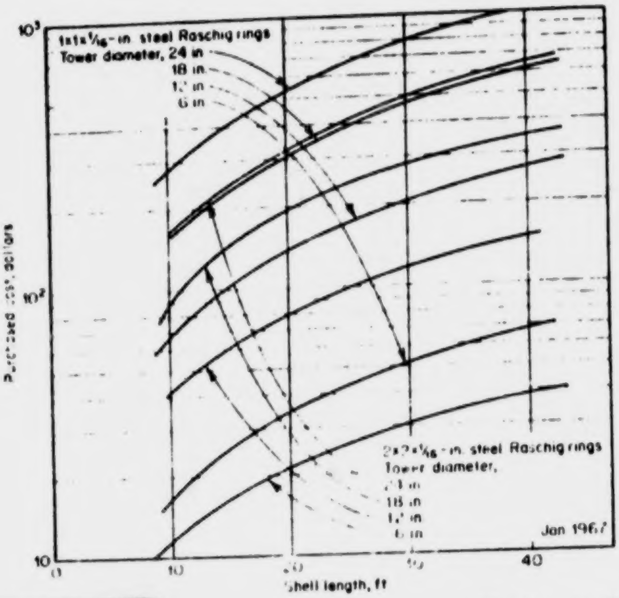
(Ref. F-8)

Figure 7

COST OF TOWERS INCLUDING INSTALLATION AND AUXILIARIES



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(Ref. F-8)

Figure 8

COST OF STEEL RASCHIG-RING TOWER PACKINGS

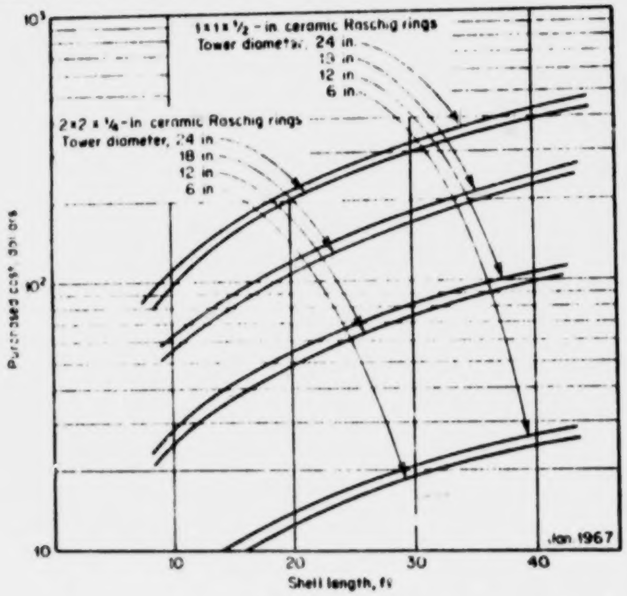

Figure 9

COST OF CERAMIC RASCHIG-RING TOWER PACKINGS

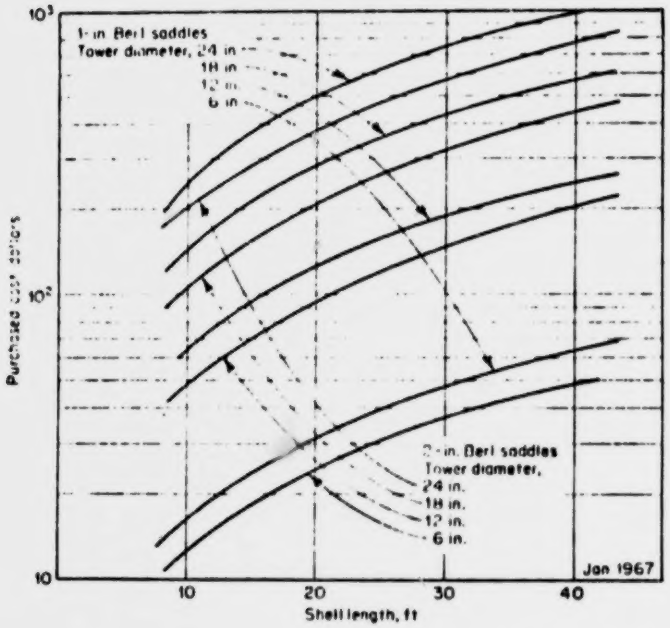

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Figure 10

COST OF BERL-SADDLE TOWER PACKINGS

5.5.2 Operating Costs

5.5.2.1 Pumping Power

The power required for pumping the liquid phase to the top of the tower is

$$\begin{aligned} \text{Power} &= L_T\, A/E_p \qquad \text{(ft lb/hr)} \\ &= \frac{8.33\ Z\ Q_L}{3.3\times10^4\ E_p} \qquad \text{(HP)} \end{aligned}$$

where

L_T is the liquid throughput in lb/hr

E_p is efficiency of the pump.

5.5.2.2 Fan Power

The power required to draw the gas through the tower is

$$\begin{aligned} \text{Power} &= G_T\, \Delta P'/E_F \qquad \text{(ft lb/hr)} \\ &= 1.57\times10^{-4}\ \Delta P\ Q_G/E_F \qquad \text{(HP)} \end{aligned}$$

where

G_T	is the gas throughput in lb/hr
$\Delta P'$	pressure drop in feet of air
E_F	efficiency of fan
ΔP	pressure drop in inches of water.

An additional pressure loss of 1 in. H_2O should also be included for pressure drop through fittings.

5.5.2.3 Power Cost

The annual cost of power is

$$\text{cost} = .746\ \theta\ P_W\ C_E$$

where

θ is the number of hours of operation per year

C_E is the cost of electricity \$/KWHR

P_W is the total power for pumping and fans.

5.5.2.4 Maintenance Cost

The annual maintenance cost is

$$\text{cost} = C_M Q_G$$

where

C_M = .02, .04, .06, \$/cfm for low, medium and high costs, respectively.

5.5.2.5 Total Operating Cost

The total annual operating cost is

$$\text{cost} = Q_G[1.57\times10^{-4}\ \theta\ \Delta P\ C_E/E_F + C_M] + 1.88\times10^{-4}\ Q_L\ Z/E_p$$

5.6 Computer Program

A computer program has been written in the Rush time-sharing system. The program is based on the design equations given above. The cost data has been entered in the form of equations. To use the program the user specifies the air flow capacity, the fraction odor removal, and the unit cost of items, such as electricity. The program performs a series of design calculations to find a liquid flow rate and column diameter for the lowest cost. It then prints out dimensions of the tower, flow rates, and costs.

5.7 Scrubber Design and Cost Estimate

A series of packed scrubber designs were calculated, using the method described above. These calculations are based on the assumption that two scrubbing liquids can be found that will between them remove all important odors. The design is also based on a conventional type of packed tower using 1-1/2 in. saddles. Other scrubber configurations may prove to be more economical.

Preliminary calculations showed that smaller packing is less economical. Plastic Tellerette packing material may be more economic and calculations could be done with this packing.

It was found economical to use the maximum gas rate that the column can handle without flooding and the maximum liquid recirculation rate for which experimental correlations are available. Under these conditions the cost of scrubbing is less than that of incineration, except when the inlet odor concentration is as high as 1000 ppm. In this case the chemicals cost raises the cost of scrubbing above that of incineration; because the incinerator can reduce a higher odor concentration simply by operating at a higher temperature. Results are summarized in Table 11.

Table 11

SCRUBBER COST SUMMARY
(Pentanal in Air) (1-1/2 in. Intalox Saddles)
Two Scrubbers in Series

Flow, CFM	Reduction Ratio Odor Concentration	Flow Rates, lb/hr sq ft Liquid	Flow Rates, lb/hr sq ft Gas	Packing Depth, ft	Tower Diameter, ft	Pressure Drop, in Water	Costs Investment, $	Costs Chemicals* $/Year	Costs Total** $/Year	Costs $/1000 CFM hr
1,000	100	569	7500	5.2	3.2	.46	8,200	7	2,370	.49
	1,000	570	7500	7.8	3.2	.69	12,180	72	3,450	.69
	100,000	570	7500	12.9	3.2	1.15	20,120	7,200	12,600	2.50
5,000	100	570	7500	5.1	7.1	.49	22,600	35	7,200	.29
	1,000	570	7500	7.7	7.1	.74	33,600	350	10,400	.41
	100,000	571	7500	12.8	7.1	1.23	55,600	35,000	50,000	2.00
25,000	100	571	7500	5.1	15.8	.49	67,400	175	24,800	.19
	1,000	571	7500	7.7	15.8	.74	99,800	1,750	35,200	.28
	100,000	571	7500	12.8	15.8	1.23	164,680	175,000	225,000	1.80

*Chemical cost based on effluent concentration .01 ppm by volume. Typical chemical cost based on reaction with NaOH at 20 cents/lb.

**Based on 5,000 hours operation per year.

6. DESIGN AND COST OF HORIZONTAL SPRAY SCRUBBER

6.1 Introduction

A new type of spray scrubber has been designed by Air Conditioning Corporation, Greensboro, North Carolina. This scrubber has been installed in a number of rendering plants and found to give satisfactory odor reduction. A drawing of one unit is shown in Figure 11. This scrubber consists of a long duct into which the plant air flows. A bank of spray nozzles is mounted near the entrance of the duct, and the scrubbing liquid is atmozed by pumping the liquid under pressure through the nozzles. At the end of the scrubber is an effective mist eliminator. Two or more units can be connected in series to make use of several scrubbing liquids. It is possible to calculate the performance by using penetration theory to calculate the mass transfer to the drops in the scrubber.

The success of this scrubber depends on the use of low air velocities such that the droplets remain in the scrubber for several seconds. Previously designed spray scrubbers either have insufficient droplet area/unit volume, or insufficient contact time. Although the nozzles point upstream, the stopping distance of droplets is such that they soon acquire the air velocity, and drift down the scrubber to the exit. Therefore the droplet contact time is only slightly longer than the air contact time in the scrubber.

Nozzles are used which give a relatively coarse spray, with a mean size of about 400 μm. The size depends slightly on water pressure and significantly on size of nozzle expressed as flowrate in Figure 12. Of course there is a distribution of droplet sizes as shown by Figure 13, but some preliminary calculations showed that the mean size can represent the behavior of the spray within 10% of the integrated average.

According to the methods of calculation used, each droplet acts independently of the others. Actually the droplets can

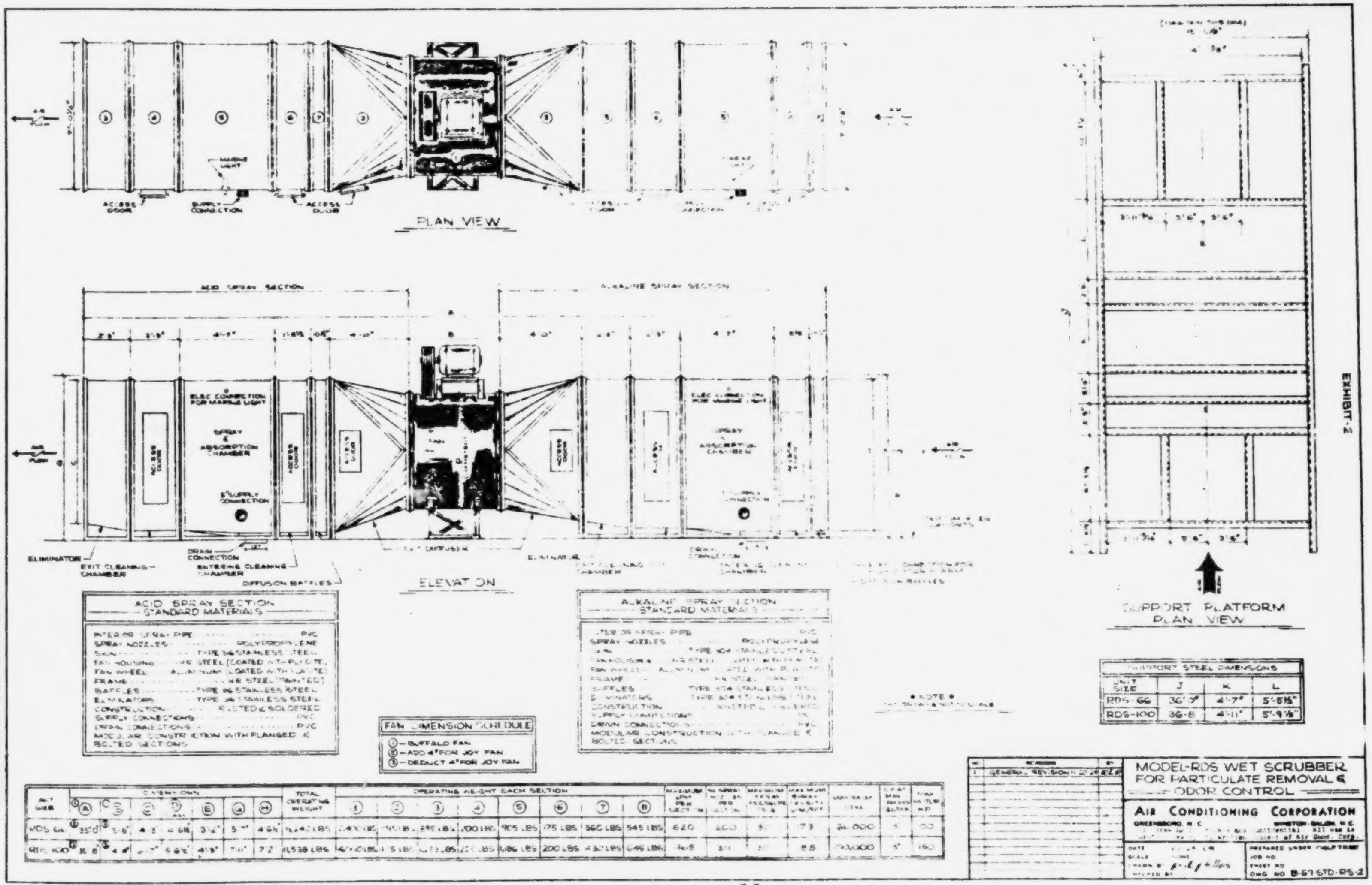


EXHIBIT-2
PLAN VIEW
ACCESS DOOR
SUPPLY CONNECTION
ACCESS DOOR
ACID SPRAY SECTION
ALKALINE SPRAY SECTION
ELEC. CONNECTION FOR MARINE LIGHT
SPRAY & ABSORPTION CHAMBER
ACCESS DOOR
2" SUPPLY CONNECTION
ELIMINATOR
EXIT CLEANING CHAMBER
DRAIN CONNECTION
ENTERING CLEANING CHAMBER
DIFFUSION BAFFLES
ELEVATION
ACID SPRAY SECTION STANDARD MATERIALS
INTERIOR SPRAY PIPE .... PVC
SPRAY NOZZLES .... POLYPROPYLENE
SKIN .... TYPE 316 STAINLESS STEEL
FAN HOUSING .... HR STEEL (COATED WITH PLASITE)
FAN WHEEL .... ALUMINUM (COATED WITH PLASITE)
FRAME .... HR STEEL (PAINTED)
BAFFLES .... TYPE 316 STAINLESS STEEL
ELIMINATORS .... TYPE 316 STAINLESS STEEL
CONSTRUCTION .... RIVETED & SOLDERED
SUPPLY CONNECTIONS .... PVC
DRAIN CONNECTIONS .... PVC
MODULAR CONSTRUCTION WITH FLANGED & BOLTED SECTIONS
FAN DIMENSION SCHEDULE
① – BUFFALO FAN
② – ADD 4" FOR JOY FAN
③ – DEDUCT 4" FOR JOY FAN
ALKALINE SPRAY SECTION STANDARD MATERIALS
INTERIOR SPRAY PIPE .... PVC
SPRAY NOZZLES .... POLYPROPYLENE
SKIN .... TYPE 304 STAINLESS STEEL
FAN HOUSING .... HR STEEL (COATED WITH PLASITE)
FAN WHEEL .... ALUMINUM (COATED WITH PLASITE)
FRAME .... HR STEEL (PAINTED)
BAFFLES .... TYPE 304 STAINLESS STEEL
ELIMINATORS .... TYPE 304 STAINLESS STEEL
CONSTRUCTION .... RIVETED & SOLDERED
SUPPLY CONNECTIONS .... PVC
DRAIN CONNECTIONS .... PVC
MODULAR CONSTRUCTION WITH FLANGED & BOLTED SECTIONS
SUPPORT PLATFORM PLAN VIEW
SUPPORT STEEL DIMENSIONS
UNIT SIZE | J | K | L
RDS-66 | 36'3" | 4'-7" | 5'-5½"
RDS-100 | 36-8 | 4'-11" | 5'-9⅛"
DIMENSIONS
TOTAL OPERATING WEIGHT
OPERATING WEIGHT EACH SECTION
RDS-66 | 35'0" | 3'-6" | 4'-3" | 4'-6⅝" | 3'½" | 5'-7" | 4'6⅝" | 5,440 LBS | 2,400 LBS | 950 LBS | 695 LBS | 200 LBS | 905 LBS | 175 LBS | 360 LBS | 545 LBS | 620 | 200 | 36,000
RDS-100 | 36'8" | 4'4" | 4'-7" | 6'6⅞" | 4'8" | 7'0" | 7'2" | 11,538 LBS | 486 LBS | 200 LBS | 430 LBS | 646 LBS | 365 | 8.5 | 150
MODEL-RDS WET SCRUBBER FOR PARTICULATE REMOVAL & ODOR CONTROL
AIR CONDITIONING CORPORATION
GREENSBORO, N. C.
WINSTON-SALEM, N. C.
GENERAL REVISION
DATE
SCALE NONE
DRAWN BY
CHECKED BY
PREPARED UNDER
JOB NO
SHEET NO
DWG NO B-67 STD-RS-2

Figure 11
WET SCRUBBER

Reproduced from best available copy.

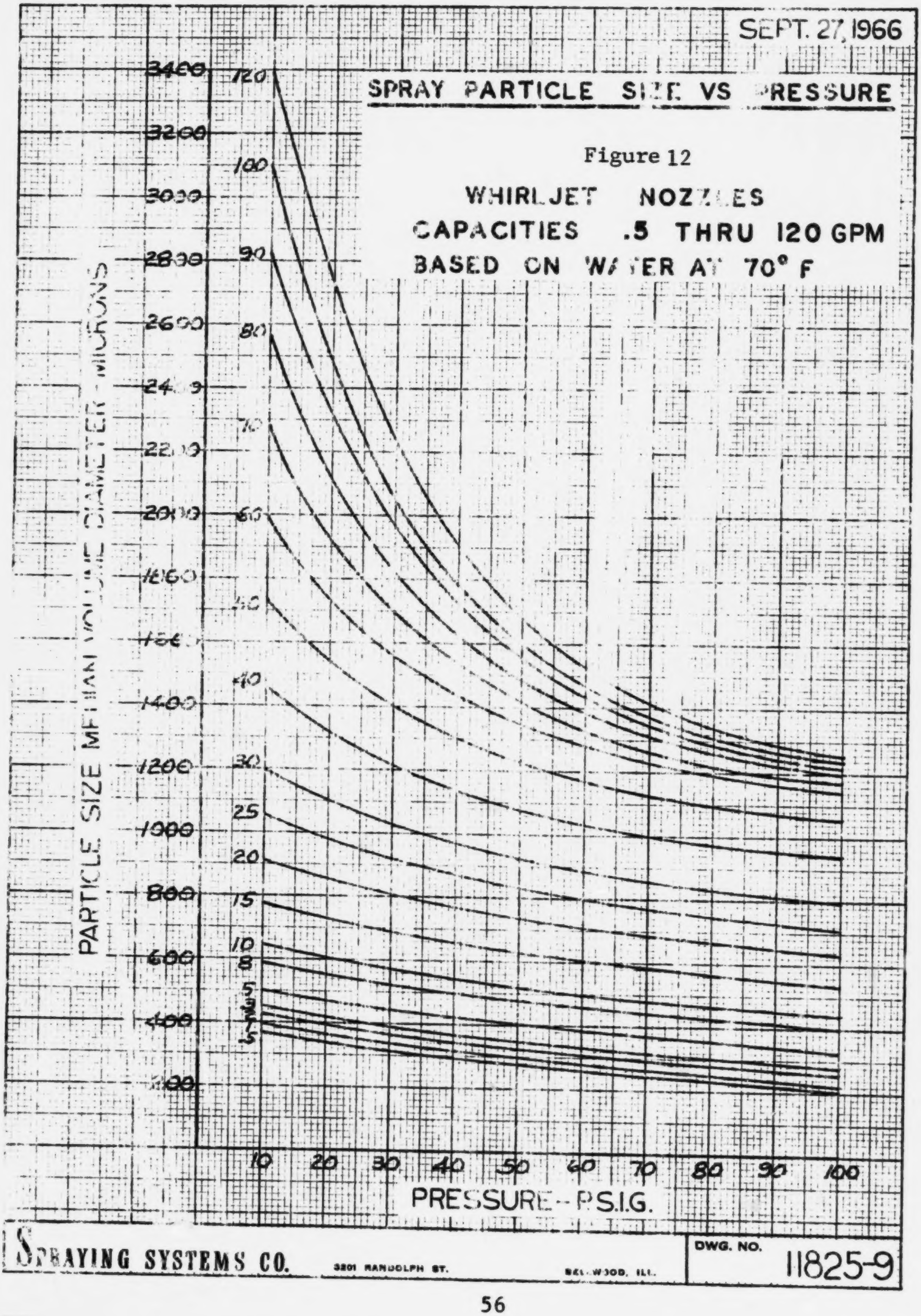
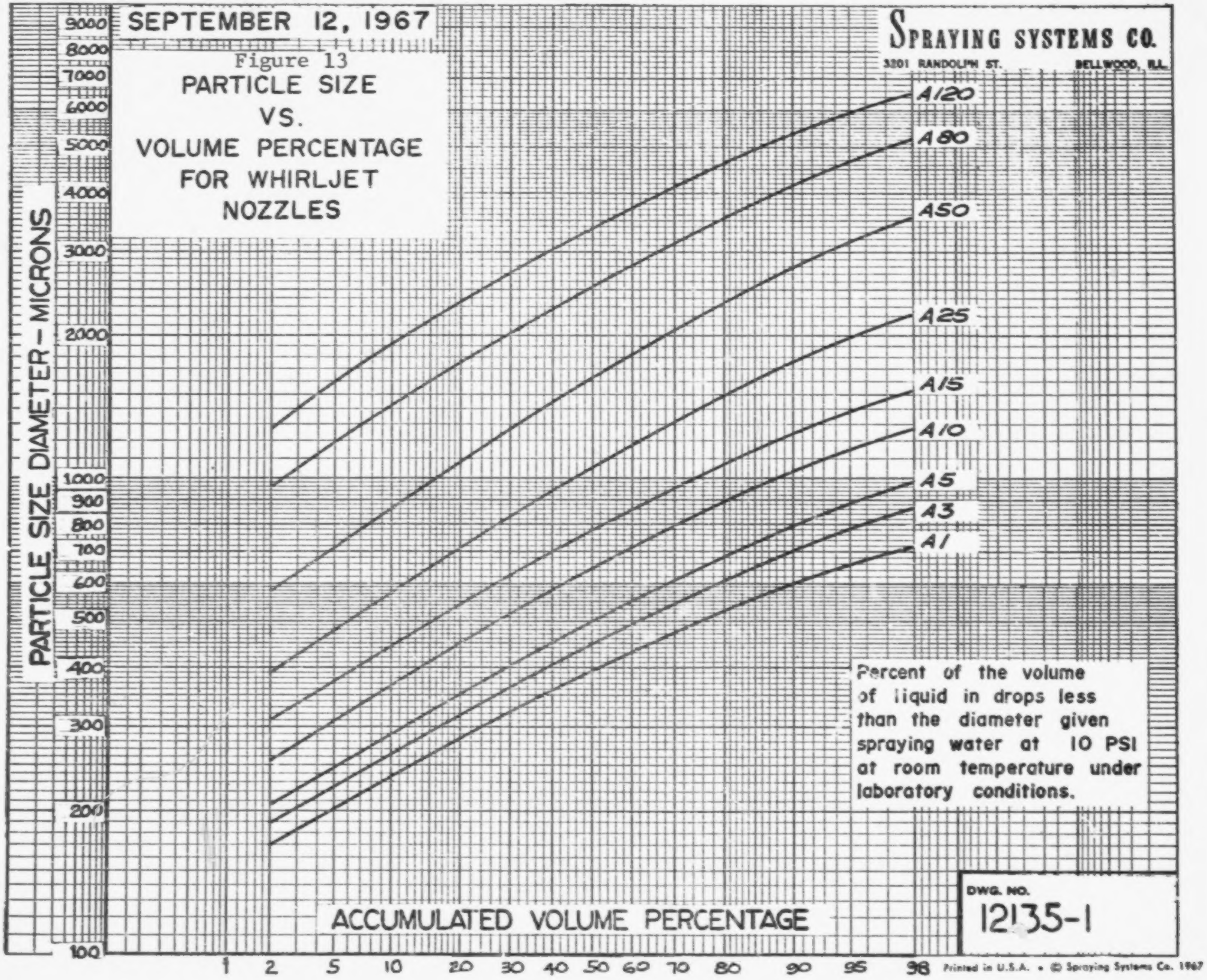

SEPT. 27, 1966
SPRAY PARTICLE SIZE VS PRESSURE
WHIRLJET NOZZLES
CAPACITIES .5 THRU 120 GPM
BASED ON WATER AT 70° F
PARTICLE SIZE MEDIAN VOLUME DIAMETER - MICRONS
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
120
100
90
80
70
60
50
40
30
25
20
15
10
8
5
3
2
1
.5
10
20
30
40
50
60
70
80
90
100
PRESSURE - P.S.I.G.
SPRAYING SYSTEMS CO.
3201 RANDOLPH ST.
BELLWOOD, ILL.
DWG. NO.
11825-9

Figure 12



SEPTEMBER 12, 1967

Figure 13
PARTICLE SIZE
VS.
VOLUME PERCENTAGE
FOR WHIRLJET
NOZZLES

collide and coalesce. This effect is computed to see if it is significant, but is not compensated for. In addition the droplets can settle and collect on the floor of the scrubber. The terminal settling velocity of 400 μm droplets in air is 3 ft/sec. This velocity cannot be directly applied to the turbulent flow conditions of the scrubber, but it suggests that the performance will be reduced if the contact time is more than a few seconds.

6.2 Nomenclature for Spray Scrubber

T	Absolute temperature, °R
a	Area available for mass transfer, surface area of drops, ft^2/ft^3
θ_c	Contact time of drops in scrubber, hr
Diff	Diffusivity of odorant vapor in air, ft^2/hr
N_0	Drop concentration at scrubber nozzles, number/ft^3
N_1	Drop concentration at scrubber outlet, number/ft
d_p	Drop diameter, mean, μm (micrometers)
d_{drop}	Drop diameter, μm
σ	Drop diameter, ft
L_{noz}	Flow of liquid per nozzle, gal/min
V_g	Gas velocity in scrubber, ft/hr
Z	Height of scrubber, ft
Y_o	Inlet concentration, mol fraction or partial pressure of odorant
X_L	Length of a scrubber stage, ft.
L	Liquid flow rate, ft^3/hr
L_{noz}	Liquid flow per nozzle, gal/min
X_x	Log of odor reduction ratio
k_g	Mass transfer coefficient, lb-mol/hr-ft^2-atm
u	Mean drop/velocity relative to gas, turbulent velocity, ft/sec
G_M	Molar gas flow rate, lb-mol/hr-ft^2
v	Molar gas volume, 359 cu ft
n_1	Number of collisions per drop per sec

N_{oza}	Number of nozzles per sq ft of scrubber cross section
N_{noz}	Number of nozzles per stage
Y_e	Outlet concentration of odorant
T	Temperature of gas stream, °R
CFM	Total air flow, cu ft/min
Gpm	Total liquid flow, gal/min
P_T	Total pressure, atm
ε	Volume fraction of space filled with drops.

6.3 Design Equations

6.3.1 Spray Droplet Area

To compute a = spray area, ft^2 droplets/ft^3 of air

drop diameter = d_p, μm (about 400 μm)

$$\text{drop volume} = \frac{\pi}{6}\left(\frac{d_p}{25400 \times 12}\right)^3 \text{ ft}^3 \qquad (38)$$

$$\text{drop area} = \pi\left(\frac{d_p}{25400 \times 12}\right)^3 \text{ ft}^2 \qquad (39)$$

$$\frac{\text{drop area}}{\text{drop volume}} = \frac{6 \times 25400 \times 12}{d_p\ (\mu m)} \text{ 1/ft} \qquad (40)$$

6.3.2 Volume of Spray

Liquid flow

$$L = L_{noz}\ \frac{\text{gpm}}{\text{nozzle}} \times N_{noz} \text{ nozzles}$$

$$\times \frac{ft^3}{\rho_L \text{ lb}} \times \frac{7.481 \text{ lb}}{\text{gal}} \times 60\ \frac{\text{min}}{\text{hr}} \qquad (41)$$

$$= ft^3 \text{ liquid/hr}$$

Spray volume/cu ft air

$$= L \frac{ft^3}{hr} \quad 60 \frac{1}{CFM} \quad \frac{hr}{ft^3}$$

$$= L_{noz} N_{noz} \frac{7.481}{\rho_L} \frac{1}{CFM} = \frac{ft^3 \text{ spray}}{ft^3 \text{ air}} \tag{42}$$

a = spray area/ft^3 air

$$a = L_{noz} N_{noz} \frac{7.481}{\rho_L} \quad \frac{1}{CFM} \quad \frac{6 \times 25400 \times 12}{d_p} \quad \frac{ft^2 \text{ spray}}{ft^3 \text{ air}} \tag{43}$$

This is independent of the length of scrubber if droplets move with the air.

6.3.3 Mass Transfer Equation

The equation for mass transfer is the same as that for a packed scrubbing tower. Only the method of calculating the mass transfer coefficient is different. This equation is given in Section 5.2.

$$\ln \frac{Y_o}{Y_e} = \frac{X_L \; k_g \; a \; P_T}{G_M} = X_x \tag{44}$$

6.3.4 Penetration Theory

The mass transfer coefficient is predicted from penetration theory based on the transient diffusion of odorant through the gas layer adjacent to each drop. The result is (Ref. 1)

$$k_g = \frac{2}{RT} \sqrt{\frac{\text{Diff}}{\pi \theta_c}} \quad \frac{\text{lb-mol}}{\text{hr-ft}^2\text{-atm}} \tag{45}$$

The contact time θ_c of droplets in air depends on the length of scrubber X_L and the gas (and droplet) velocity.

$$\theta_c = \frac{X_L}{V_{gas}} \quad \frac{\text{ft}}{\text{ft/hr}} = \frac{X_L \text{ cross-sectional area}}{60 \text{ CFM}}$$

$$= \frac{X_L\ W\ Z}{60 \text{ CFM}} \quad \text{ft}^3 \quad \frac{\text{hr}}{\text{ft}^3} \tag{46}$$

6.3.5 Scrubber Design

The required performance of the scrubber is expressed by the quantity X_x. This can be related to scrubber dimensions by substituting 45 and 46 into 44. The ideal gas law is also used.

$$\frac{P_T}{RT} = \frac{1}{v} = \frac{1}{359 \text{ ft}^3} \tag{47}$$

$$G_M \ \frac{\text{lb mol}}{\text{hr-ft}^2} \times \frac{359 \text{ ft}^3}{\text{lb mol}} \times \frac{T}{460} = \frac{\text{ft}^3 \text{ liquid}}{\text{hr-ft}^2}$$

$$= \frac{60 \text{ CFM}}{W\ Z} \tag{48}$$

$$X_x = \frac{X_L\ k_g\ a\ P_T}{G_m}$$

$$= X_L\ 2\ a\ \sqrt{\frac{\text{Diff CFM}}{\pi\ X_L\ W\ Z}}\ \frac{1}{359}\ \frac{W\ Z}{60\ \text{CFM}}\ \frac{359\ T}{460}$$

$$= \frac{2\ T\ a}{460}\ \sqrt{\frac{\text{Diff}\ X_L\ W\ Z}{60\ \pi\ \text{CFM}}} \qquad (49)$$

This is the basic design equation.

We could now design the scrubber length X_L for a given width and height Z to achieve the desired reduction ratio. When this is done, impossible lengths result. Instead, we fix the length $X_L = 29$ ft, as is done by Air Conditioning Corporation, and vary the height Z. In doing so, we allow the number of nozzles per unit cross-sectional area N_{oza} to remain constant; the total number increases with height Z. The liquid flow per nozzle L_{noz} is also fixed, so changing the height changes the liquid flow and increases the droplet area. It also decreases the air velocity and increases the contact time. As a result the capacity depends on $Z^{3/2}$. These substitutions are not detailed here, but they are included in the design computer program.

The flow rate per nozzle L_{noz} is another variable that affects the design, and hence the scrubbing cost. The program provides for reading in 4 values of L_{noz}; it computes the scrubber design and cost for each, and chooses the most economic one. Other variables, such as spray nozzle pressure affect droplet size and power. These can be explored by trial calculations with the program.

6.4 Cost Equations

Costs of each component of equipment and operating costs are similar to those used for the packed tower scrubber, except the coefficients are different. These equations are included in the computer program.

6.5 Droplet Collision Rate

The drop collision rate can be estimated from the kinetic gas theory, for example by Loeb.[4] The only difficulty is in estimating the mean turbulent velocity of the drops with respect to the gas. It is this component of velocity which causes them to collide.

From kinetic gas theory the collision rate

$$n_1 = \text{no. of collisions per sec per drop}$$

$$= \frac{2 \pi u N \sigma^2}{\varepsilon} \tag{50}$$

The fraction reduced per unit time is

$$\frac{dN}{N} = \frac{1}{2} n_1 \, d\theta = \frac{\pi u N \sigma^2}{\varepsilon} \tag{51}$$

This integrates to

$$\frac{1}{N_1} = \frac{1}{N_0} = \frac{\pi u \sigma^2 \theta_c}{2 \varepsilon} \tag{52}$$

Assume that $u = \frac{1}{2} V_g$

$$u \theta_c = \frac{1}{2} X_L$$

$$\frac{1}{N_1} = \frac{1}{N_0} + \frac{\pi \sigma^2 X_L}{4 \varepsilon} \tag{53}$$

The fraction of space occupied by drops is

$$\varepsilon = \frac{L}{CFM} = \frac{G_{pm}\ 7.481}{\rho_L\ CFM} \tag{54}$$

The initial number of droplets per cu ft N_0 is

$$N_0 = \frac{L}{\frac{\pi}{6}\ CFM \left(\frac{D_{drop}}{25400 \times 12}\right)^3} \tag{55}$$

The number left at the end of the scrubber is

$$N_1 = \frac{1}{\frac{1}{N_0} + \frac{\pi X_L}{2\varepsilon} \left(\frac{D_{drop}}{25400 \times 12}\right)^2} \tag{56}$$

Both N_0 and N_1 are listed by the computer program. In most cases the decrease is a small fraction of N_0, but it could be large if a high liquid flow rate is chosen.

6.6 Design and Cost Estimates

Tables 12A to 12H present results of calculations with the design computer program. All of these examples are for 2-stage units. The cost of this method of scrubbing appears to be about 1/4 that by other methods when expressed in $/1000 cfm-hr. The effect of flow capacity on unit cost is very small as shown in the first four tables. These tables correspond to cost data kindly provided by Air Conditioning Corporation, and they check these values within 15%. The cost decreases somewhat with lower reduction ratios, as shown in Tables 12E, 12F, and 12G, and the method even competes with carbon adsorption for treating ventilation air. Table 12H is computed for an amortization factor of 0.1 corresponding to 15 year life at 7% interest.

Table 12A

DESIGN AND COST OF SPRAY SCRUBBING

```
   NØZZLES/SQ FT   LENGTH   UNITS/SERIES   DDRØP UM   NØZZLE PSI
        4.0          29.0         2.0        400.0       15.0
 GPM/NØZZLE
     1.000      2.200      5.000     10.000

     CØEFFICIENTS AND EXPØNENTS FØR CØST CØRRELATIØNS
         SCRUBBER                     FAN                 PUMP         NØZZLES
   176.000       .800       .290       .800     11.500       .600      5.000

                      UNIT CØSTS FØR SCRUBBER SYSTEM
 PØWER      MAINTENANCE      CHEMICALS      NØZZLES      AMØRTIZATIØN
 $/KWH        $/CFM          $/CFM-YR         $ EA          FACTØR
  .015         .005            .014          5.000           .250

 FLØW RATE   CØNCENTRATIØN    HENRY    SCHMIDT NØ    TEMPERATURE     HRS/YR
    CFM      INLET  ØUTLET                            DEGREES F
   25000. 1000.000 1.000       0.          0.               70.       5500

           INTERMEDIATE VALUES DURING ØPTIMIZATIØN
    ANNUAL CØST   CAPITAL   TIM-SEC   HEIGHT   GPM/NØZ   FT2/FT3   NØ     N1
      21858.9     50438.0     6.2      11.1      1.0       7.8 1367028 1150861
       31946.
      20486.2     37340.9     3.7       6.6      2.2      10.1 1777898 1349237
       27954.
      20918.9     28629.5     2.1       3.8      5.0      13.3 2337459 1508854
       26645.
      22569.7     23846.0     1.3       2.4     10.0      16.7 2944946 1573407
      20918.9     28629.5     2.1       3.8      5.0      13.3 2337459 1508854
       26645.


                 ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
              THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
       SCRUBBER LENGTH      SCRUBBER HEIGHT      TØTAL FLØW RATES
            FEET                  FEET          GAS(CFM)    LIQUID(GPM)
            29.0                  3.8           25000.0          607.3

          NØZZLES          BANKS          DDRØP UM          UNITS/SERIES
           121.              1.              400.                 2.

            PRESSURE DRØP      FAN HØRSEPØWER      PUMP HØRSEPØWER
                3.000              16.821          198.754


                   CAPITAL CØSTS FØR SCRUBBER SYSTEM
       SHELL      NØZZLES      FAN      PUMP      EXTERNALS       TØTAL
      14541.      1215.       1025.     1076.     10773.         28630.

                    ANNUAL CØST FØR SCRUBBER SYSTEM
 AMØRTIZATIØN   PØWER   MAINTENANCE   CHEMICALS   TØTAL    $/1000CFM-HR
     7157.      12061.    1000.          700.     20919.          .17
```

Table 12B

EFFECT OF AIR FLOW

```
                 UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      CHEMICALS      NOZZLES      AMORTIZATION
$/KWH         $/CFM         $/CFM-YR        $ EA           FACTOR
 .015          .005           .014         5.000         .250

FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
  CFM        INLET  OUTLET                            DEGREES F
 38000. 1000.000 1.000         0.           0.              70.

          INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  N3   N1
    32227.4     72169.5     6.2      16.9      1.0      7.8 1367056 1150877
     46661.
    30463.5     53668.5     3.7      10.0      2.2     10.1 1777935 1349251
     41197.
    31332.4     41364.4     2.1       5.8      5.0     13.3 2337508 1508863
     39605.
    33954.4     34604.5     1.3       3.6     10.0     16.7 2945008 1573410
    31332.4     41364.4     2.1       5.8      5.0     13.3 2337508 1508863
     39605.


              OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER LENGTH      SCRUBBER HEIGHT       TOTAL FLOW RATES
          FEET                  FEET           GAS(CFM)    LIQUID(GPM)
          29.0                  5.8            38000.0          923.1

        NOZZLES          BANKS          DDROP UM          UNITS/SERIES
          185.             1.              400.                 2.

          PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                  3.000        25.569            303.427


                 CAPITAL COSTS FOR SCRUBBER SYSTEM
     SHELL       NOZZLES       FAN       PUMP      EXTERNALS       TOTAL
    20328.       1846.        1433.      1383.     16374.          41364.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS    TOTAL    $/1000CFM-HR
    10341.      18407.   1520.             1064.    31332.           .16
```

Table 12C

EFFECT OF AIR FLOW

```
                        UNIT CØSTS FØR SCRUBBER SYSTEM
PØWER      MAINTENANCE       CHEMICALS       NØZZLES      AMØRTIZATIØN
$/KWH         $/CFM          $/CFM-YR         $ EA           FACTØR
 .015         .005             .014          5.000           .250

FLØW RATE   CØNCENTRATIØN    HENRY    SCHMIDT NØ    TEMPERATURE
  CFM        INLET  ØUTLET                           DEGREES F
 66000. 1000.000 1.000        0.          0.               70.

            INTERMEDIATE VALUES DURING ØPTIMIZATIØN
   ANNUAL CØST   CAPITAL   TIM-SEC   HEIGHT   GPM/NØZ   FT2/FT3  NØ   N1
      54116.9   116035.8      6.2     29.3      1.0      7.8 1367094 1150899
       77324.
      51677.2    86832.3      3.7     17.3      2.2     10.1 1777984 1349271
       69044.
      53588.8    67417.2      2.1     10.0      5.0     13.3 2337573 1508875
       67072.
      58353.5    56746.0      1.3      6.3     10.0     16.7 2945089 1573413
      53588.8    67417.2      2.1     10.0      5.0     13.3 2337573 1508875
       67072.


              ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
          THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
     SCRUBBER LENGTH      SCRUBBER HEIGHT      TØTAL FLØW RATES
          FEET                 FEET          GAS(CFM)    LIQUID(GPM)
          29.0                 10.0          66000.0         1603.3

       NØZZLES          BANKS          DDRØP UM         UNITS/SERIES
         321.             1.             400.               2.

          PRESSURE DRØP      FAN HØRSEPØWER      PUMP HØRSEPØWER
                3.000           44.409           531.935


                CAPITAL CØSTS FØR SCRUBBER SYSTEM
     SHELL      NØZZLES      FAN      PUMP     EXTERNALS      TØTAL
    31616.      3207.       2229.    1926.    28439.         67417.

                       ANNUAL CØST FØR SCRUBBER SYSTEM
AMØRTIZATIØN   PØWER   MAINTENANCE   CHEMICALS   TØTAL    $/1000CFM-HR
   16854.     32246.    2640.          1848.     53589.        .16
```

Table 12D

EFFECT OF AIR FLOW

```
                         UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      CHEMICALS      NOZZLES      AMORTIZATION
$/KWH        $/CFM          $/CFM-YR        $ EA            FACTOR
 .015         .005           .014          5.000           .250

FLOW RATE   CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
  CFM       INLET  OUTLET                           DEGREES F
 100000. 1000.000 1.000       0.          0.              70.

             INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  NO      N1
    80460.3    166207.8     6.2      44.4      1.0       7.8 1367123 1150915
    77323.4    124998.1     3.7      26.2      2.2      10.1 1778021 1349285
    102323.
    80568.3     97612.0     2.1      15.2      5.0      13.3 2337621 1508885
    100091.
    87961.9     82557.3     1.3       9.6     10.0      16.7 2945150 1573415
    80568.3     97612.0     2.1      15.2      5.0      13.3 2337621 1508885
    100091.


                  OPERATING CONDITIONS OF TOWER-CALCULATED
             THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
        SCRUBBER LENGTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
             FEET                 FEET          GAS(CFM)     LIQUID(GPM)
             29.0                 15.2          100000.0          2429.3

          NOZZLES          BANKS          DDROP UM          UNITS/SERIES
            486.             1.             400.                 2.

             PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
                   3.000           67.286            815.024


                  CAPITAL COSTS FOR SCRUBBER SYSTEM
       SHELL      NOZZLES      FAN      PUMP      EXTERNALS       TOTAL
      44083.      4859.      3108.     2472.     43090.         97612.

                        ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS    TOTAL    $/1000CFM-HR
    24403.      49365.    4000.           2800.     80568.          .16
```

Table 12E

EFFECT OF AIR FLOW

```
                     UNIT CØSTS FØR SCRUBBER SYSTEM
 PØWER     MAINTENANCE      CHEMICALS       NØZZLES       AMØRTIZATIØN
 $/KWH        $/CFM         $/CFM-YR          $ EA            FACTØR
  .015         .005           .014           5.000             .250

 FLØW RATE    CØNCENTRATIØN    HENRY     SCHMIDT NØ    TEMPERATURE
    CFM       INLET  ØUTLET                              DEGREES F
 150000.  1000.000 1.000        0.           0.               70.

            INTERMEDIATE VALUES DURING ØPTIMIZATIØN
   ANNUAL CØST   CAPITAL   TIM-SEC   HEIGHT   GPM/NØZ   FT2/FT3   NØ      N1
    119371.7    236396.5     6.2      66.6      1.0       7.8 1367150 1150931
    115250.8    178684.4     3.7      39.4      2.2      10.1 1778057 1349299
    120453.2    140350.3     2.1      22.8      5.0      13.3 2337669 1508894
      148523.
    131690.9    119277.2     1.3      14.3     10.0      16.7 2945210 1573417
    120453.2    140350.3     2.1      22.8      5.0      13.3 2337669 1508894
      148523.


                 ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
             THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
     SCRUBBER LENGTH      SCRUBBER HEIGHT      TØTAL FLØW RATES
          FEET                  FEET          GAS(CFM)     LIQUID(GPM)
          29.0                  22.8          150000.0        3644.0

       NØZZLES          BANKS          DDRØP UM          UNITS/SERIES
         729.             1.             400.                2.

         PRESSURE DRØP       FAN HØRSEPØWER       PUMP HØRSEPØWER
                 3.000          100.929            1242.514

                  CAPITAL  CØSTS FØR SCRUBBER SYSTEM
      SHELL       NØZZLES       FAN      PUMP     EXTERNALS       TØTAL
     60975.       7288.        4299.     3153.    64635.        140350.

                      ANNUAL CØST FØR SCRUBBER SYSTEM
 AMØRTIZATIØN    PØWER   MAINTENANCE   CHEMICALS    TØTAL     $/1000CFM-HR
     35088.      75166.    6000.         4200.     120453.          .16
```

Table 12F

EFFECT OF ODOR REDUCTION RATIO

```
                   UNIT CØSTS FØR SCRUBBER SYSTEM
PØWER    MAINTENANCE     CHEMICALS      NØZZLES      AMØRTIZATIØN
$/KWH       $/CFM        $/CFM-YR         $ EA          FACTØR
 .015        .005          .014          5.000           .250

FLØW RATE   CØNCENTRATIØN    HENRY    SCHMIDT NØ   TEMPERATURE
   CFM      INLET  ØUTLET                           DEGREES F
 150000.  100.000 1.000        0.          0.             70.

          INTERMEDIATE VALUES DURING ØPTIMIZATIØN
  ANNUAL CØST   CAPITAL   TIM-SEC   HEIGHT   GPM/NØZ   FT2/FT3   NØ     N1
    99471.4    203028.4     4.7      50.8      1.0      5.9 1043317   940428
    96051.0    156926.5     2.8      30.0      2.2      7.7 1356893  1145003
    99867.0    126293.9     1.6      17.4      5.0     10.1 1783951  1351608
     125126.
   108378.3    109454.3     1.0      10.9     10.0     12.8 2247585  1490695
    99867.0    126293.9     1.6      17.4      5.0     10.1 1783951  1351608
     125126.


              ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
          THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
      SCRUBBER LENGTH      SCRUBBER HEIGHT     TØTAL FLØW RATES
           FEET                  FEET         GAS(CFM)    LIQUID(GPM)
           29.0                  17.4         150000.0        2780.9

        NØZZLES          BANKS         DDRØP UM         UNITS/SERIES
          556.             1.            400.                2.

          PRESSURE DRØP      FAN HØRSEPØWER      PUMP HØRSEPØWER
                3.000         100.929             937.383

              CAPITAL CØSTS FØR SCRUBBER SYSTEM
     SHELL       NØZZLES      FAN      PUMP     EXTERNALS      TØTAL
    49117.       5562.       4299.     2681.    64635.       126294.

                   ANNUAL CØST FØR SCRUBBER SYSTEM
AMØRTIZATIØN    PØWER   MAINTENANCE   CHEMICALS    TØTAL    $/1000CFM-HR
    31573.      58094.    6000.          4200.     99867.          .13
```

Table 12G

EFFECT OF ODOR REDUCTION RATIO

```
                        UNIT CØSTS FØR SCRUBBER SYSTEM
 PØWER     MAINTENANCE       CHEMICALS       NØZZLES       AMØRTIZATIØN
 $/KWH        $/CFM          $/CFM-YR         $ EA            FACTØR
  .015         .005            .014           5.000            .250

FLØW RATE   CØNCENTRATIØN    HENRY    SCHMIDT NØ    TEMPERATURE
   CFM      INLET  ØUTLET                             DEGREES F
 150000.   10.000 1.000       0.          0.               70.

             INTERMEDIATE VALUES DURING ØPTIMIZATIØN
   ANNUAL CØST   CAPITAL   TIM-SEC   HEIGHT   GPM/NØZ   FT2/FT3  NØ   N1
     75955.0    160723.6     3.0      32.0      1.0      3.7  657233   629886
     73384.0    129297.6     1.8      18.9      2.2      4.9  854769   796RV
       99244.
     75532.5    108406.6     1.0      10.9      5.0      6.4 1123793   997211
       97214.
     80769.2     96923.6      .6       6.9     10.0      8.0 1415857 1178419
     75532.5    108406.6     1.0      10.9      5.0      6.4 1123793   997211
       97214.


                  ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
              THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
        SCRUBBER LENGTH      SCRUBBER HEIGHT      TØTAL FLØW RATES
             FEET                 FEET          GAS(CFM)    LIQUID(GPM)
             29.0                 10.9          150000.0        1751.8

          NØZZLES          BANKS           DDRØP UM          UNITS/SERIES
           350.              1.              400.                 2.

            PRESSURE DRØP       FAN HØRSEPØWER       PUMP HØRSEPØWER
                  3.000          100.929             582.375


                  CAPITAL CØSTS FØR SCRUBBER SYSTEM
      SHELL       NØZZLES      FAN      PUMP      EXTERNALS        TØTAL
     33937.       3504.       4299.     2032.     64635.         108407.

                     ANNUAL CØST FØR SCRUBBER SYSTEM
 AMØRTIZATIØN    PØWER   MAINTENANCE    CHEMICALS    TØTAL     $/1000CFM-HR
    27102.      38231.    6000.           4200.     75532.          .10
```

Table 12H

EFFECT OF AMORTIZATION PERIOD AND OPERATING HOURS

```
                    UNIT CØSTS FØR SCRUBBER SYSTEM
 PØWER      MAINTENANCE      CHEMICALS      NØZZLES      AMØRTIZATIØN
 $/KWH         $/CFM         $/CFM-YR         $ EA          FACTØR
  .015          .005           .014          5.000           .100

 FLØW RATE   CØNCENTRATIØN    HENRY    SCHMIDT NØ    TEMPERATURE   HRS/YR
   CFM       INLET  ØUTLET                            DEGREES F
  66000. 1000.000 1.000       0.           0.               70.    3000

          INTERMEDIATE VALUES DURING ØPTIMIZATIØN
   ANNUAL CØST  CAPITAL   TIM-SEC  HEIGHT   GPM/NØZ   FT2/FT3  NØ   N1
     32587.5    116035.8     6.2     29.3      1.0       7.8 1367094 1150899
      55795.
     33556.1     86832.3     3.7     17.3      2.2      10.1 1777984 1349271
      50923.
     37026.9     67417.2     2.1     10.0      5.0      13.3 2337573 1508875
      50510.
     41905.8     56746.0     1.3      6.3     10.0      16.7 2945089 1573413
     37026.9     67417.2     2.1     10.0      5.0      13.3 2337573 1508875
      50510.


                  ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
             THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL
       SCRUBBER LENGTH      SCRUBBER HEIGHT      TØTAL FLØW RATES
            FEET                 FEET           GAS(CFM)    LIQUID(GPM)
            29.0                 10.0           66000.0        1603.3

          NØZZLES          BANKS          DDRØP UM          UNITS/SERIES
            321.             1.             400.                2.

            PRESSURE DRØP      FAN HØRSEPØWER      PUMP HØRSEPØWER
                   3.000           44.409          530.935


                   CAPITAL CØSTS FØR SCRUBBER SYSTEM
      SHELL       NØZZLES      FAN      PUMP     EXTERNALS       TØTAL
     31616.       3207.       2229.     1926.     28439.         67417.

                      ANNUAL CØST FØR SCRUBBER SYSTEM
 AMØRTIZATIØN    PØWER   MAINTENANCE    CHEMICALS    TØTAL    $/1000CFM-HR
     6742.       25797.    2640.          1848.      37027.          .14
```

Tests of a two-stage unit have been reported by a member company of NRA, and an odor reduction of 85% was reported using soda ash and sodium bisulfite. The results cannot be directly compared because the flow rates are not known.

6.7 References

1. Mass Transfer Operations (Second Edition), Robert E. Treybal, McGraw-Hill, 1955, p. 51 ff.
2. Perry's Chemical Engineers Handbook (Fourth Edition), Perry, Chilton, Kirkpatrick, McGraw-Hill, 1963.
3. Private Communication, Harold A. Ogletree, Air Conditioning Corporation, June, 1972.
4. Loeb, L. B., The Kinetic Theory of Gases, Second Edition, McGraw-Hill, N.Y., 1934, p. 36, 39, 95.

7. EXPERIMENTAL SCRUBBING INVESTIGATIONS

A preliminary economic analysis of various odor removal methods, based on literature data and reports of member companies, indicated that scrubbing with reactive liquids was the most promising method. This method was therefore chosen for experimental study.

The performance and cost of a scrubbing system depends partly on the design of the system, and partly on finding one or more chemical reagents that can effectively react with the important odor constituents present. These problems can be separately studied. Two types of scrubbing reaction experiments were conducted and, in addition, design studies were done to find the most effective and economic scrubbing system.

The two types of scrubbing reaction studies were an exploratory bubbler experiment method and a packed column scrubber method. One focuses attention on the capacity of the reagent to consume odorant, and the other measures the rate of reaction with relatively fresh reagent. Both criteria are important for selecting reagents.

A list of odorants used in bubbler or scrubber experiments is given in Table 13.

A list of scrubbing liquids was also selected and is shown in Table 14. This list includes a number of liquids previously suggested by others, some that are in actual use and a number that we have thought of. We have included several that are used as oxidizing or reducing agents in paper pulp bleaching or other industrial purification operations.

Table 13

LIST OF ODORANTS FOR SCRUBBING TESTS

	MW	Density, g/cc	MP, °C	BP, °C
Sulfides				
n-Propyl sulfide (dipropyl sulfide)	118.2	.839		142-3
Dimethyl disulfide (methyl sulfide)	94.19	1.057		116-8
Propylene sulfide				
Amines				
Trimethylamine	59.11	gas	-117.	2.9
Tert-butylamine	73.14	.698	-67.	45.2
n-Butylamine	73.14	.739	-50.	77.8
Dimethyl pyrazine	108.14	.990	15	155.
Quinoline	129.15	1.095	-15.6	237.
Acids				
Butyric	88.1	.949	-47.	155.
Aldehydes				
n-Pentanal (n-valeric aldehyde)	86.13	.819	-92.	103.4
Alcohol				
n-Pentanol (n-amyl alcohol)	88.15	.818	-78.9	138.1
Ketone				
Butandione (diacetyl)	86.19	.981	-4.	87-8
Unsaturated Alkane				
Heptadiene 2,5 (simulant for dimethyl pentadiene)	96.17	.733		107.

Table 14

LIST OF SCRUBBING SOLUTIONS SCREENED

Sodium hydroxide
Sodium carbonate
Sodium bisulfite
Sodium hypochlorite (representing free chlorine)
Hydrogen peroxide
Potassium permanganate
Potassium persulfate
Hydrochloric acid
Nitric acid
Ozone solution
Copper sulfate
Ferric chloride
Barium chloride
Aluminum chloride

8. EXPLORATORY BUBBLER SCRUBBING REACTIONS

8.1 Experimental Method

In the bubbler exploratory method a mixture of several odorants is dissolved in 200 ml of water in a glass bubbler equipped with a fritted glass disperser. Air is drawn through the bubbler at a rate of about 50 ml/min for 1 min. This air is drawn through the sampling loop by means of an aspirator. After 1 min the air sample in the loop is transferred to the chromatograph. The process is repeated several times to establish the effluent odorant concentrations with no reagent present. Then the bubbler is opened and a 50 ml quantity of scrubbing liquid is added. Sampling is repeated several times. The ratio of effluent concentration before and after adding scrubbing liquid is a measure of the reactivity of the liquid for each odorant. The mass transfer behavior of the bubbler is effectively cancelled out by this procedure, and only the reactivity is measured.

The quantity of each odorant added to the bubbler depends on the solubility of the odorant in water. A quantity is added which gives a sufficient vapor pressure to obtain a reasonable peak size with the chromatograph. Thus, amyl alcohol is relatively soluble and requires 20 mg, while propyl sulfide is relatively insoluble and requires only a few μg. In fact, the quantity of propyl sulfide used is so small that an appreciable fraction of it is vaporized by the air stream and its effluent concentration decreases with time even when there is no reaction. In the presence of this gradual decrease, only large reductions by reaction can be definitely identified.

At the other extreme is butyric acid which is miscible with water in all proportions. One gram of butyric acid in 250 ml water has so low a vapor pressure that it cannot be measured by chromatograph. Although the bubbler experiment cannot be done with butyric acid, this result shows that water alone is an effective scrubbing liquid and no other is needed.

In order to inject small quantities of odorants with a microsyringe, stock solutions were made up in an inert water-soluble liquid. The solvents used and concentrations are listed in Table 15.

8.2 Experimental Results

The experimental results with several odorants are presented in Tables 16-18. The first experiment shows the decreases in effluent concentration obtained with water for 4 successive samples. The numerical values represent area under the chromatogram in square inches. Previous calibrations indicated that these areas are approximately 3 times the concentration in ppm by volume.

In the second experiment 4 samples of the effluent were taken to assure steady conditions, and then 2 more samples were taken after nitric acid was added. In the right column of the table, the reductions are expressed as a percent of initial effluent concentration. This method is followed for each of the other tests.

The method was slightly different in Table 18. Here the odorants were added to 100 ml water, and the first 2 concentrations measured in air drawn through the sample. Then the reagent was added in another 100 ml water, and the remaining concentrations were measured. Comparison of the results with those for water still gives a measure of the reduction ratio. The procedure is apparently less accurate, although it was necessary for use with ozone water.

Since several amines were found in the rendering plant odors without definitely establishing their identity, experiments were tried with various representative butyl amines as well as trimethylamine. The formulas of these amines are shown in Figure 14.

Table 15

AMOUNTS OF ODORANTS ADDED TO BUBBLER

		Stock Solution	Added to Bubbler	Solvent
Series #1				
1.	Amyl alcohol	16 mg/ml	20 ml	Water
2.	Dipropyl sulfide	60 mg/ml	0.1 ml	Ethyl ether
3.	Valeraldehyde	4 mg/ml	1.0 ml	Ethylene glycol
Series #2				
4.	Trimethylamine	Varies	1-2 ml	Water
5.	Heptadiene	60 mg/ml	Added to amyl alcohol	
6.	Amyl alcohol	2 ml of solution #5 is diluted to 100 ml in water		
7.	Butanedione	50 mg/ml	5 ml	Ethylene glycol

Table 16

EXPLORATORY EXPERIMENTS
REACTIONS OF ODORANTS WITH SCRUBBING LIQUIDS

Odorant	Concentrations in Effluent Air from Bubbler - Arbitrary Units (3 x ppm)						Reduction by Reagent
	Water						
Test:	1	2	3	4			
Valeraldehyde	110	97	92	95			Nearly constant effluent
Propyl sulfide	1248	596	506	394			Gradually vaporizes
Amyl alcohol	55	53	50	55			Nearly constant effluent
	Water				Nitric Acid Added (5%)		
Test:	1	2	3	4	5	6	
Valeraldehyde	22	7	9	15	6	7	Decreased within expt. error
Propyl sulfide	7875	1948	-	778	61	49	90%
Amyl alcohol	153	73	100	123	61	59	40%
	Water			Hydrochloric Acid Added (5%)			
Test:	1	2	3	4	5		
Valeraldehyde	15	9	14	10	13		None
Propyl sulfide	9288	784	434	70	41		50-90%
Amyl alcohol	139	110	116	68	77		30%
	Water		Sodium Hydroxide Added (5%)				
Test:	1	2	3	4			
Valeraldehyde	44	10	11	7			Slight
Propyl sulfide	614	116	119*	14			90%
Amyl alcohol	152	123	805	848			Increased
	Water			Sodium Carbonate Added (5%)			
Test:	1	2	3	4	5		
Valeraldehyde	75	62	78	62	77		None
Propyl sulfide	1875	1320	713	278	263		Uncertain
Amyl alcohol	523	657	811	683	770		None
	Water			Hypochlorite (1%)			
Test:	1	2	3	4			
Valeraldehyde	35	23	23	2			90%
Propyl sulfide	558	271	85	0			99+
Amyl alcohol	104	102	168	210			None
15 min. peak)				small			
17 min. peak)				small			
	Water		Hypochlorite Added (1%)				
Test:	1	2	3	4	5		
Valeraldehyde	33	28	22*	2	1		90%
Propyl sulfide	435	201	tr	0	0		99+
Amyl alcohol	211	177	242	107	152		None
15 min.					small		
17 min.					small		
	Water		Hypochlorite Added (.5%)				
Test:	1	2	3	4			
Valeraldehyde	32	41	23	9			75%
Propyl sulfide	1540	1038	tr	0			99+
Amyl alcohol	200	229	149	141			25%?
17 min.				small			
	Water		Potassium Permanganate (.6%)				
Test:	1	2	3	4			
Valeraldehyde	32	29	tr	tr			99+
Propyl sulfide	1510	995	0	tr			99+
Amyl alcohol	147	181	102	229			None
1.8 min.			tr	31			
16 min.				tr			
18 min.				tr			

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Table 16 (cont.)

Odorant	Concentrations in Effluent Air from Bubbler - Arbitrary Units (3 x ppm)						Reduction by Reagent
	Water			Potassium Permanganate (.6%) + NaOH (1%)			
Test*	1	2	3	4	5		
Valeraldehyde	65	43	38	2	tr		98%
Propyl sulfide	1970	893	348	tr	0		99+
Amyl alcohol	758	563	635	927	882		Increased
	Water		Hydrogen Peroxide Added (5%)				
Test:	1	2	3	4			
Valeraldehyde	61	65	tr	6			90%
Propyl sulfide	690	366	11	1			99+
Amyl alcohol	433	507	400	407			None
	Water		Ozone Water (~1%)				
Test:	1	2	3	4			
Valeraldehyde	68	61	64	69			None
Propyl sulfide	1361	495	1596	636			None
Amyl alcohol	449	454	407	409			None
	Water			Sodium Persulfate Added (satd)			
Test:	1	2	3	4	5		
Valeraldehyde	62	69	70	59	51		20%
Propyl sulfide	1839	1513	981	317	tr		~99%
Amyl alcohol	-	567	601	525	501		None
	Water		Sodium Bisulfite Added (5%)				
Test:	1	2	3	4			
Valeraldehyde	90	111	0	0.1			99.5%
Propyl sulfide	2510	1238	506	219			None
Amyl alcohol	758	775	666	612			None
	Water				Ferric Chloride Added (5%)		
Test:	1	2	3	4	5	6	
Valeraldehyde	89	51	89	73	86	80	None
Propyl sulfide	2616	1221	1256	765	402	236	None
Amyl alcohol	743	463	825	902	893	910	None
	Water		Copper Sulfate (5%)				
Test:	1	2	3	4			
Valeraldehyde	70	82	24	25			70%
Propyl sulfide	2277	1138	197	150			80%
Amyl alcohol	735	802	242	230			70%
	Water			Copper Sulfate (5%) pH3			
Test:	1	2	3	4	5		
Valeraldehyde	41	44	41	31	28		20%
Propyl sulfide	1269	712	396	188	101		Uncertain
Amyl alcohol	281	318	310	244	199		Uncertain
	Water		Barium Chloride Added (5%)				
Test:	1	2	3	4			
Valeraldehyde	42	39	41	37			None
Propyl sulfide	1475	906	489	251			None
Amyl alcohol	249	323	307	307			None
	Water			Aluminum Chloride Added (5%)			
Test:	1	2	3	4	5		
Valeraldehyde	90	71	70	68	81		None
Propyl sulfide	904	850	372	169	61		None
Amyl alcohol	515	499	515	910	610		None

---

*In some cases the vapor space may not have been purged of effluent when first sample was chromatographed.

Table 17

BUBBLER EXPERIMENTS

Chromatograph Areas (Proportional to Concentration)

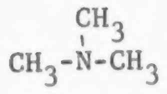
	(1)	(2)	(3)	(4)	Percent Removal By Reagent
21/6/72-2	Water Blank Run for O_3 Experiments (Odorants in 200 ml Water)				
Heptadiene	7683	6957			
Propylene Sulfide	2898	2159			
Dimethyldisulfide	1532	1599			
Amyl Alcohol	57	82			
21/6/72-5	Water Blank (Duplicate of Above)				
Heptadiene	7735	2625	332	105	
Propylene Sulfide	2601	2160	1865	1627	
Dimethyldisulfide	1661	1417	958	790	
Amyl Alcohol	80	77	77	76	
21/6/72-3	Ozone in Distilled Water				
Heptadiene	5930	1377	249	74	
Propylene Sulfide	1933	1758	1421	1205	
Dimethyldisulfide	1430	923	742	629	
Amyl Alcohol	55	58	56	58	
21/6/72-4	Ozone in Distilled Water				
Heptadiene	6797	4818	249	104	None
Propylene Sulfide	1915	1755	1705	1425	None
Dimethylsulfide	1123	1256	835	718	None
Amyl Alcohol	47	48	73	71	None
23/6/72-1	Ozone - pH ~1 (1 ml Conc. HCl/200 ml Water)				None
Heptadiene	5900	2275	501		None
Propylene Sulfide	1500	1912	1647		None
Dimethyldisulfide	916	1022	803		None
Amyl Alcohol	12	62	42		None
23/6/72-3	Ozone - pH ~1 (1 ml Conc. HCl/200 ml Water)				None
Heptadiene	7915	4957	827		
Propylene Sulfide	2383	1911	1718		
Dimethyldisulfide	1487	1470	964		
Amyl Alcohol	53	56	60		
23/6/72-2	Ozone - pH ~12 (10 g $NaHCO_3$ + 1 g Na_2CO_3/200 ml Water)				None
Heptadiene	7335	4600	652		
Propylene Sulfide	2439	2403	2091		
Dimethyldisulfide	1563	1543	952		
Amyl Alcohol	81	80	83		
New PK @ 2.4 min	-	134	962		

Table 18

BUBBLER EXPERIMENTS
Chromatograph Areas (Proportional to Concentration)

	(1)	(2)	(3)	(4)	(5)	Percent Removal By Reagent
26/6/72-1	Odorants in 100 ml Water, Further Diluted with 100 ml Water After Run 1					
Heptadiene	6248	1925	133	53		
Propylene Sulfide	2856	1776	854	626		
Dimethyldisulfide	1652	1115	458	364		
Amyl Alcohol	108	100	46	44		
26/6/72-2	Odorants in 100 ml Water, Further Diluted with 100 ml Water After Run 2					
Heptadiene	6066	1480	92	47		
Propylene Sulfide	2684	2258	930	686		
Dimethyldisulfide	1395	1380	501	390		
Amyl Alcohol	94	-	84	76		
27/6/72-1	HCl ~5%					
Heptadiene	6768	2702	297	73		0
Propylene Sulfide	3085	2169	1274	1043		0
Dimethyldisulfide	2000	1287	632	567		0
Amyl Alcohol	102	48	73	74		0
27/6/72-2	NaOH ~5%					
Heptadiene	6561	4252	722	105		0
Propylene Sulfide	3105	2259	2036	1026		0
Dimethyldisulfide	1562	1899	1216	630		0
Amyl Alcohol	130	127	201	184		0
27/6/72-3	NaOCl ~2.5%					
Heptadiene	5867	5454	1052	79	16	Uncertain
Propylene Sulfide	3530	2230	Trace	Trace	0.2	>99.9
Dimethyldisulfide	1474	1747	0.4	Trace	Trace	>99.9
Amyl Alcohol	267	174	155	-	145	0
28/6/72-3	NaOCl ~2.5% (Duplicate of Above)					
Heptadiene	6424	4326	820	156		0
Propylene Sulfide	2720	2686	Trace	Trace		>99.9
Dimethyldisulfide	1644	1809	Trace	Trace		>99.9
Amyl Alcohol	122	141	141	157		0
28/6/72-1	H_2O_2 ~5%					
Heptadiene	7684	5204	1719	614	344	0
Propylene Sulfide	3227	2617	470	6	Trace	>99.9
Dimethyldisulfide	2067	1791	739	182	82	60.
Amyl Alcohol	103	117	66	36	57	Uncertain
28/6/72-2	K MnO_4 ~1/2 Sat @ 22°C					
Heptadiene	6103	4554	134	8		80.
Propylene Sulfide	2565	2659	Trace	1		>99.5
Dimethyldisulfide	1258	1653	Trace	Trace		>99.9
Amyl Alcohol	79	127	77	60		0

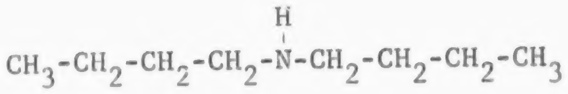
Trimethylamine



$$CH_3\text{-}\overset{CH_3}{N}\text{-}CH_3$$

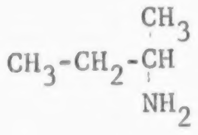
n-Butylamine $CH_3\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}NH_2$

Di-n-butylamine



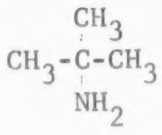
$$CH_3\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}\overset{H}{N}\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_3$$

sec-Butylamine



$$CH_3\text{-}CH_2\text{-}\overset{CH_3}{\underset{NH_2}{CH}}$$

tert-Butylamine



$$CH_3\text{-}\overset{CH_3}{\underset{NH_2}{C}}\text{-}CH_3$$

Figure 14

AMINES

Dibutylamine decomposes in water and gives five peaks of lower molecular weight. One of these is n-butylamine. A large amount of dibutylamine remains unreacted.

Tertiary butylamine is the most stable. It decomposes slowly, giving 2 smaller peaks at higher retention times. n-Butylamine decomposes rapidly, being reduced to 1/10 in 15 min. One very broad product peak is produced at higher retention time. Sec-butylamine and isobutylamine also react rapidly to give several peaks. Consequently, tert- and di-butylamines were chosen for further bubbler tests.

Results of all of the bubbler experiments are summarized in Table 19. Water is the first and simplest reagent. Butyric acid and amyl alcohol are so soluble that water is an effective scrubbing liquid for them. Various amines appear to react extensively in water, so it may effectively scrub them too. Dimethyl pyrazine reacts in water and could not be detected after the bubbler. Quinoline appeared to react in the bubbler, or the sample loop or the chromatograph, giving a very broad peak, but the result is uncertain.

Acids such as hydrochloric, nitric, and probably sulfuric react with amines, and have a slight effect on dipropyl sulfide and amyl alcohol. Acids cannot be considered as effective scrubbing liquids. Likewise alkalis are poor scrubbing liquids. Although sodium carbonate is used industrially for odor scrubbing, its action may be attributed almost entirely to the water rather than to the alkali. Sodium hydroxide will be converted to carbonate by absorbing CO_2 from the air scrubbed.

The most effective reagents are the strong oxidizers: sodium hypochlorite, hydrogen peroxide, potassium permanganate and sodium persulfate. All of these remove sulfides, although hydrogen peroxide is less effective on dimethyl disulfide. Permanganate is more effective on pentanal than the other oxidants, and is the only oxidant to react with heptadiene-2,5. Permanganate is more effective in neutral than in alkaline solution.

Sodium hypochlorite is the cheapest of these oxidants and it should therefore be the first choice. Chlorine water might also be considered; hypochlorite is a solution of chlorine in alkali. Chlorine was tried, but it oxidized the chromatograph column and prevented analysis of odorants. With special precautions it could be tried in a scrubber test. Hypochlorite has the advantage that the chlorine is not lost in the effluent gas.

Various metal salts were also tried; copper sulfate was the only one that offered any promise.

A hypochlorite solution can be made by releasing chlorine gas into the scrubber while a sodium hydroxide solution is being circulated. The oxidizing power of the solution can be maintained by bleeding chlorine gas into the scrubber continuously. Chlorine in bulk is very inexpensive. If the chlorine is not added continuously, the hypochlorite will soon decompose, and it will not be effective. Only occasionally will it be necessary to make up a fresh solution, if this method of replenishment is followed. The chlorine can also be produced on the site by electrolysis of salt solution; equipment for this process is commercially available.

Table 19

SUMMARY OF BUBBLER EXPERIMENT RESULTS-PERCENT REMOVAL BY REAGENT

Odorant	Water	Hydrochloric Acid 5%	Nitric Acid 5%	Sodium Hydroxide 5%	Sodium Carbonate 5%	Sodium Hypochlorite			Potassium Permanganate		Hydrogen Peroxide 5%	Ozone Water			Sodium Persulfate Satd.	Sodium Bisulfite 5%	Ferric Chloride 5%	Copper Sulfate		Barium Chloride 5%	Aluminum Chloride 5%
						2.5%	1%	.5%	.6% Neutral	+1% NaOH		~1%	pH 1	pH 12				5%	5% pH 3		
Di-n-propyl sulfide	Vaporizes*	50-90	90	90	Uncertain		"99+	>'99	>"'99	>99	>99	None			~99	None	None	80	Uncertain	None	None
Dimethyl disulfide	Vaporizes*	None		None		>99.9			>99.9		60	None	None	None							
Propylene sulfide	Vaporizes*	None		None		≥99.9			>99.5		>99.9	None	None	None							
n-Pentanal (n-valeric aldehyde)	*	None	Slight	Slight	None		90	75	99+	98	90	None			20	99.5	None	70	20	None	None
n-Pentanol (n-amyl alcohol)	Soluble*	30	40	Increased	None		None	Uncer-tain	None	Increased	None	None	None	None	None	None	None	70	Uncertain	None	None
Butanedione																					
Heptadiene 2,5	Vaporizes*	None		None		None			80		None	None	None	None							
Butyric acid	>99.9																				
Dimethyl pyrazine	>90																				
n-Butylamine	*																				
tert-butylamine	*	>99					>95				>99										
Di-n-butylamine	*	>95					95				90										
Quinoline	Uncertain																				
Isobutylamine	Reacts																				
sec-Butylamine	Reacts																				

*Used as standard for comparison.

' = Product peak appeared.

9. SCRUBBING EXPERIMENTS

9.1 Experimental Gas Scrubbing System

An experimental gas scrubbing system was designed and constructed. The system provides data on the performance of a variety of scrubbing liquids with representative odorants found in rendering effluents. It also provides data on the relative rates of mass transfer and chemical reaction with the scrubbing liquids. This information can be used for design of scrubbing systems for plant applications.

We have chosen a conventional packing for the scrubber column (1/2-in. Intalox saddles) because there is extensive data on the mass transfer coefficients for this packing and we wish to compare our results to other published data for which chemical reaction rate is not a limitation.

The column was designed using this data and the gas scrubbing computer program described in Section 5. With the height of packing used and the chosen flow rates, the column should be capable of reducing any given odorant concentration 90% if the reagent reacts very fast with the odorant, so that only mass transfer from the gas to the liquid controls the scrubbing. Removals of more than 90% are suspect, since the column should not be capable of greater performance unless the flow rates are altered.

The data obtained from this experimental system will be useful for designing other types of scrubbers even though 1-1/2-in. Intalox saddles may not be the most economical packing.

The experimental scrubbing system is shown in Figure 15. It consists of two similar packed columns, the first of which humidifies the air supply to simulate typical rendering plant effluent conditions. Odorants are metered into the air stream after humidification. Odor generators consist either of a lecture bottle of the gaseous odorants or saturators. A saturator is a bottle containing glass beads wet with a

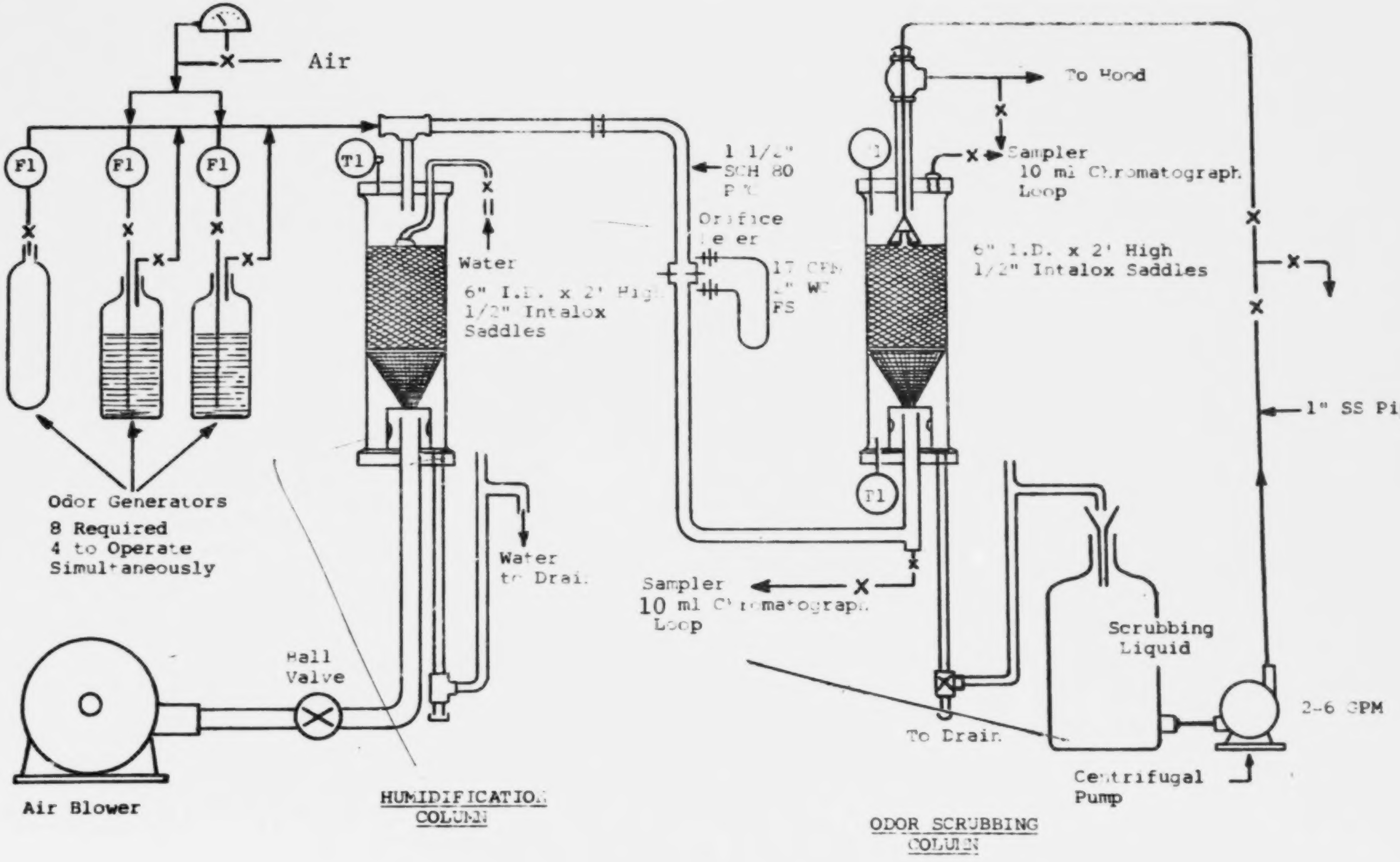


Fig. 15 LABORATORY ODOR SCRUBBING SYSTEM

liquid odorant. Air is metered through this wet packing at a rate to supply the desired concentration after it is diluted with the main air stream. Toward the end of the project it was found that ordinary gas washing bottles with a fritted glass disperser worked better than the bottles with glass beads.

The main air flow is supplied by a blower with excess capacity, both as to volume and pressure. The flow is throttled by a ball valve and metered by a standard orifice. The pressure drop across the orifice is measured by an inclined manometer.

The columns consist of 6-in. I.D. Pyrex glass pipe. The packing is supported by a cone-shaped screen resting on a stainless cap. The scrubbing liquid is sprayed onto the top of the packing. A 2-ft packing depth is designed to reduce the odorant concentrations by a factor of 10 at the flow rates chosen. The scrubbing liquid is made up in a 5-gal polyethylene bottle and pumped by a polypropylene centrifugal pump to the top of the packing. Exhaustion tests were not made, since information on reagent eventual capacity was obtained from the bubbler tests. Only in the case of potassium permanganate was there any evidence of exhaustion of the reagent during a 1-hr test.

The main air line is constructed of polyvinyl chloride pipe, while the scrubbing liquid line is constructed of stainless steel pipe and polyethylene tubing. Saturator bottles are glass and supply tubing is of stainless steel.

Eight odorant generators are fabricated but rotameters and connections are supplied for use of 6 simultaneously. It is thought best not to mix acidic and aminic odorants in the same run, since these will react in the gas phase if concentrations are high enough. Some other combinations of odorants were also found to react and had to be run separately. The concentrations used in the tests are similar to those encountered in strong rendering plant effluents.

A chromatograph is incorporated in the system in a manner which permits the sampling of the odorant stream at either the inlet or the outlet of the scrubber column. A sample of known volume may be withdrawn from the odorant stream by means of aspiration and isolated in a gas sampling loop, from which it is swept directly into the chromatograph with an adequate volume of carrier gas. A Perkin-Elmer Model 881 dual column gas chromatograph with differential flame ionization detector is currently being used. The columns are 1/8-in. x 10-ft Teflon-lined aluminum packed with 100/120 mesh SP-1000. Helium is used as carrier gas at a flow rate of 60 cc/min. Inlet and detector temperatures are approximately 200°C and the sample loop is maintained at 100°C. Initial column temperature is 60°C and is programmed to 180°C at various rates depending on the particular mixture of odorants being monitored.

9.2 Results of Scrubbing Experiments

Several series of scrubbing experiments were done, using a different combination of several odorants in each series. For each experiment several samples were taken from the bottom of the scrubbing column to assure steady conditions. Then water was sprayed onto the column and a sample was taken from the top of the column. Another sample was taken from the bottom to check for steady conditions. The scrubbing reagent to be tested was then added to the water and samples were taken again at the top and the bottom of the column.

The ratio of chromatograph areas at top and bottom of the column gives the reduction ratio of concentration due to the scrubber. The data for water were of interest to assure reproducibility of results and also because water is a potential scrubbing liquid.

The sensitivity of the chromatograph was calibrated from time to time by injecting known quantities of odorants from a microsyringe into the chromatograph. The concentrations in Table 20 to 28 are expressed as μg/ml, based on the chromatograph

Table 20

SCRUBBING OF VALERALDEHYDE

Scrubbing Conditions			Concentration, μg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
			.48		
NaOH 5%	.6	16		.48	0
		16	.57		
			.57		
NaOH 5%	.7	16		.50	10
NaOH 5%	.7	16		.45	15
		16.4	.0057		
			.0097		
			.0107		
Water	.6			.0054	50
			.0113		
NaOCl 1%	.6			.0092	10
			(Background .0017)		
(19/5/72)					
			.0102		
			.0102		
Water	.6	16.5		.0065	50
			.0120		
Sodium Bisulfite	.6			trace	>90
			.129		
(23/5/72)					
		16.5	.0051		
			.0036		
Water	.6			.0043	0
			.0044		
H_2O_2 3%	.6			0	>90
H_2O_2 3%	.6			.0005	>90
			.0057		
			.0042		
			.0053		

Table 20 (cont.)

Scrubbing Conditions			Concentration, μg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	at Top of Scrubber	Ratio
(25/5/72)					
		16.4	.0143		
Water	.6			.010	30
			.0113		
$KMnO_4$ 3%				.0071	40
$KMnO_4$ 3%				.0063	
$KMnO_4$ 3%				.0057	
			.0088		
(31/5/72)					
		16.5	.008		
			.0156		
			.013		
			.016		
			.012		
			.014		
Water	.6			.0087	40
			.013		
$KMnO_4$	.6			.0068	50
$KMnO_4$	.6			.0092	30
			.015		
		16.5	.012		
			.023		
			.021		
Water	.6			.0135	30
			.020		
HCl 5%	.6			.026	0
			.018		
(2/6/72)					
		16.2	.018		
			.018		
Water	.6			.011	40
NaOH 5%	.6			.013	30
			.018		

Table 21

SCRUBBING OF DIPROPYL SULFIDE

Scrubbing Conditions			Concentration, µg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
		16	.16		
NaOH 5%	.6			.17	0
			.16		
			.18		
NaOH 5%	.7		.18	.18	0
NaOH 5%	.7			.20	
		16.3	.029		
			.028		
			.031		
Water	.6			.028	5
			.031		
NaOCl 1%	.6				>90
(19/5/72)					
		16.4	.028		
			.030		
Water	.6			.033	0
			.037		
Sodium Bisulfite	.6			.034	0
			.037		
(23/5/72)					
		16.5	.023		
			.018		
Water	.6			.021	0
			.021		
H_2O_2 3%	.6			.020	0
				.019	
			.024		
			.018		
(25/5/72)					
		16.4	.042		
Water	.6			.040	0
			.039		

Table 21 (cont.)

Scrubbing Conditions			Concentration, μg/ml Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
$KMnO_4$ 3%				.028	25
$KMnO_4$ 3%				.030	
$KMnO_4$ 3%				.032	
			.037		
(31/5/72)					
		16.5	.053		
			.056		
			.054		
			.042		
			.055		
Water	.6			.054	0
			.048		
$KMnO_4$	.6			.040	10
$KMnO_4$	.6			.042	
			.050		
(1/6/72)					
		16.5	.049		
			.045		
			.066		
Water	.6			.056	10
			.054		
HCl 5%	.6			.053*	0
			.054		
(2/6/72)					
		16.2	.069		
			.070		
Water	.6			.065	10
NaOH 5%	.6			.067	0
			.065		

*Strong odor of mercaptan and H_2S in scrubbing liquid.

Table 22

SCRUBBING OF AMYL ALCOHOL

Scrubbing Conditions			Concentration, µg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
		5.2	.43		
NaOH 5%	.6	5.2		.45	0
		5.2	.47		
		5.2	.42		
NaOH 5%	.7	5.2		.47	0
NaOH 5%	.7	5.2		.43	
		15.6	.40		
			.48		
NaOH 5%	.7	15.4		.08	80
After 30 min	.7	15.5		.20	50
After 1 hr	.7	15.5	.40	.28	30
		16.4	.23		
			.25		
			.25		
			(Background .007)		
Water	.6			.017	90
			.26		
NaOCl 1%	.6			.051	80
(19/5/72)					
		15.3	.23		
			.26		
Water	.6			.010	60
			.30		
Sodium Bisulfite	.6			.067	75
			.31		
(23/5/72)					
		16.5	.16		
			.14		
Water	.6			.038	75
			.18		

Table 22 (cont.)

Scrubbing Conditions			Concentration, µg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
H_2O_2 3%	.6			.032	75
H_2O_2 3%	.6			.064	
			.21		
			.16		
			.19		
(25/5/72)					
		16.4	.27		
Water	.6			.031	85
			.26		
$KMnO_4$ 3%	.6			.051	75
$KMnO_4$ 3%	.6			.058	
$KMnO_4$ 3%	.6			.16	40
			.28		
(31/5/72)					
		16.5	.31		
			.25		
			.31		
Water	.6			.016	50
			.30		
$KMnO_4$ 3%	.6			.039	85
$KMnO_4$ 3%	.6			.12	60
			.34		
(1/6/72)					
		16.5	.31		
			.32		
			.39		
Water	.6			.041	85
			.36		
HCl 5%	.6			.073	80
			.36		
(2/6/72)					
		16.2	.32		
			.35		
Water	.6			.035	90
NaOH 5%	.6			.10	70
			.40		

Table 23

SCRUBBING OF BUTYRIC ACID

	Scrubbing Conditions		Concentration, μg/ml	
			Chromatograph	
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber
		15	1.5	
NaOH 5%	.6	15		trace
NaOH 5%	.6	15		0
		15	1.1	
NaOH 5%	.7	15		trace
NaOH 5%	.7	15		trace
		22	.67	
		22	.59	

Table 24

SCRUBBING OF BUTANEDIONE

	Scrubbing Conditions		Concentration, μg/ml Chromatograph	
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber
		16	.11	
		16	.14	
NaOH 5%	.6	16		trace
NaOH 5%	.6	16		trace
NaOH 5%	.6	16		trace
		16	.13	

Table 25

SCRUBBING OF TRIMETHYLAMINE

Scrubbing Conditions			Concentration, μg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber	Ratio
		15	.75		
		15	.83		
NaOH 5%	.6	15		Off scale	
NaOH 5% 30 min	.6	15		.98	0
NaOH 5%		15		1.40	0
1 hr		15	.90		
		15	.14		
			.20		
			.14		
			.14		
			.10		
			.060		
Water	.6	15		.0018	97
$KMnO_4$	.6	15		.00006	>90
$KMnO_4$	.6			0	
			.14		
		15	.24		
			.52		
			.21		
			.19		
			.23		
			.28		
Water	.6			.00046	>90
NaOCl 2.5%	.6			.0028	>90
			.18		
(31/5/72)					
		16.5	.23		
			.28		
Water	.6			.0003	>90
			.29		
$KMnO_4$	.6			tr?	>90
$KMnO_4$	.6			tr?	>90
			.29		

Table 25 (cont.)

Scrubbing Conditions			Concentration, μg/ml		
			Chromatograph		
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At top of Scrubber	Ratio
(1/6/72)					
		16.5	.12		
			.28		
			.38		
Water	.6			.03?	90
			.38		
HCl 5%	.6			.0015	>90
			.40		
(2/6/72)					
		16.2	.28		
			.33		
Water	.6			.0006	>90
NaOH 5%	.6			.37	0
			.35		

Table 26

SCRUBBING OF DIMETHYL DISULFIDE

Scrubbing Conditions			Concentration, μg/ml Chromatograph	
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber
		15	.40	
			.28	
Water	.6	15		.22
$KMnO_4$	.6	15		.12
$KMnO_4$	.6	15		.08
			.08	
		15	1.5	
			1.4	
Water	.6			1.2
NaOCl 2.5%	.6			.64
			.17	

Table 27

SCRUBBING OF HEPTADIENE

Scrubbing Conditions			Concentration, μg/ml	
			Chromatograph	
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber
		15	.104	
			.92	
			.65	
			.55	
Water	.6	15		.295
$KMnO_4$	.6	15		.143
$KMnO_4$	.6	15		.111
			.168	
– – – –				
			.604	
			.111	
			.0814	
			.117	
			.115	
Water	.6	15		.119
Water	.6	15		.129
			.118	
			.121	
H_2O_2	.6	15		.127
H_2O_2	.6	15		.137
			.129	
– – – –				
			.29	
			.29	
			.28	
			.25	
Water				No reduction
NaOCl 2.5%	.6			.21
		15	.27	

Table 28

SCRUBBING OF TERT-BUTYLAMINE

Scrubbing Conditions			Concentration, μg/ml	
			Chromatograph	
Material	Liquid Flow, gal/min	Air Flow, CFM	At Bottom of Scrubber	At Top of Scrubber
		15	43.29	
			61.89	
			77.39	
			70.50	
			82.19	
Water	.6			Broad
Water	.6			.007
			54.36	
			51.08	
H_2O_2 5%	.6			.47
H_2O_2	.6			.28
		15	13.44	

peak areas and these calibrations. For Tables 23 and 24 the calibrations were not determined by injection, but were determined by calculating the vapor pressure from the saturator and dividing by the air dilution ratio. This method of calibration is less accurate. In any case it is the reduction ratio that is of most interest.

Results of the scrubber experiments are summarized in Table 29. Sodium hypochlorite, NaOCl, appears to be the most effective reagent on a broad spectrum of odorants. Permanganate, which appears slightly better in bubbler tests, behaved less well on some odorants, perhaps because of a slower reaction rate. Decomposition of permanganate was apparent, a brown stain of manganese dioxide product being formed on the column packing. Sodium bisulfite is specific to aldehydes, as was expected. Sodium hydroxide and acids are not much better than water, although they might be worth trying in tests to determine the life of the scrubbing solutions.

On the basis of these results the main reagent should be sodium hypochlorite. If two scrubbing stages are needed, the first could be water, followed by hypochlorite, provided that the spent water can be disposed of without causing an odor problem. Or, the first liquid could be hypochlorite, followed by either permanganate, hydrogen peroxide, a second stage of hypochlorite, or an acid. An acid is effective on amines and it increases the solubility of alcohols.

The bubbler test results (in Table 19, page 87) gave higher odor removals than the corresponding scrubber tests in Table 29. This was expected since the scrubber is limited by mass transfer as well as by chemical reaction rate. The fraction removed by a scrubbing tower is determined by its height and it is possible to design a scrubbing tower to achieve higher reduction rates.

Table 29

SCRUBBER REMOVAL, %

	Valeraldehyde	Dipropyl Sulfide	Amyl Alcohol	Trimethyl-amine	Butyric Acid	Butanedione	Tert-Butyl amine	Heptadiene	Dimethyl Disulfide
Water	30	0	80-90	80-90			>90	0	10
NaOCl, 1%	10	>90	80	>90				20	50
H_2O_2, 3%	>90	0	75				>90	0	slight
Potassium Permanganate, 3%	30	10-25	40-80	>90				25	20-75
Sodium Bisulfite, 5%	>90	10	75						
HCl, 5%	0	0	80	>90					
Sodium Hydroxide, 5%	10-30	0	0-60	0	>90	>90	>90		

10. IDENTIFICATION OF ODORANTS

10.1 Kovats Indices of Odorants

Since the first project on the identification of odorants was completed, a new type of chromatographic column has become available, the SP-1000 column. Samples from a rendering plant were obtained to make a few additional measurements in the hope of identifying amines and sulfides which were not specifically identified in the first project. Vapor samples were passed through a 10-ft SP-1000 column and major peaks were introduced into the mass spectrometer. The process was repeated using a Pennwalt 223 column, which is suited to separations of amines. A number of compounds were tentatively identified but the identification could not be checked because the Kovats indices were not determined. Since then, Kovats indices have been determined for a few pure compounds on another project and the results are given in Table 30. It appears that the Kovats indices are not greatly different from those determined on a Carbowax 20M column. Published Kovats indices for the Carbowax column are given in Table 31. By comparison of these data it may be seen that the identifications appear reasonable.

10.2 Second Mass Spectrometer Identification Series

The new results are presented in Tables 32 and 33. Since several hydrocarbons were identified by mass spectrometer, these can be used to fix the Kovats index at several points in the tables.

10.3 Identification of Odorous Peaks

On another project, samples were taken from a variety of rendering plants using specially developed chromatographic adsorber samplers. Some of these were measured for odor level by a trained panel, while others were analyzed by gas chromatograph. Then a computer regression analysis was done to determine which peaks could be correlated with the odor intensity from different

Table 30

KOVATS INDICES FOR SOME SULFIDES, AMINES AND ACIDS ON SP-1000 AND CARBOWAX 20 COLUMNS

Compound	Kovats Index 20% Carbowax 20M	Kovats Index 10% SP-1000
Methyl mercaptan	658	
Ethyl mercaptan	750	705
Propyl mercaptan	842	
Diethyl sulfide	890	925
Butyl mercaptan	942	975
Thiophene	1034	
Pentyl mercaptan	1042	1048
Dipropyl sulfide	1051	1083
Dimethyl disulfide	1110	
Diallyl sulfide	1142	
Dibutyl sulfide	1258	
Diethyl disulfide	1275	
Heptyl mercaptan	1280	1285
Dihexyl sulfide	1695	
Butyl amine	Not effective	947
Propyl amine	Not effective	857
Allyl amine		882
Isobutyl amine		1112
Hexyl amine		1597
Propionic acid		1502
Butyric acid		1567
Valeric acid		1690
Heptanoic acid		1950
Propanal		700
Pentanal		1010
Hexanal		1100
Heptanal		1205
Ethanol		920
Propanol		1015
Isopropanol		950
Butanol		1155
Pentanol		1230
Acetone		770
2,3 Butanedione		1015
Mesityl oxide		1115
3-Heptanone		1195
3-Methyl tetrahydrofuran		870
Toluene		1130
m-Dichlorobenzene		1460

Table 31

KOVATS INDICES OF CLASSES OF COMPOUNDS ON CARBOWAX 20M COLUMN

	V_g		I_x	
	120°	160°	120°	160°
METHANOL	14.7	5.5	862	847
ETHANOL	16.9	6.2	833	869
PROPANOL	31.0	10.5	1000	986
ISOPROPANOL	16.0	6.0	883	862
BUTANOL	56.0	17.5	1111	1101
ISOBUTANOL	41.5	13.6	1055	1045
S-BUTANOL	28.6	10.0	986	975
T-BUTANOL	13.8	5.2	857	830
CYCLOPROPYL CARBINOL	91.3	27.3	1203	1201
PENTANOL	100	28.9	1223	1215
ISOPENTANOL	79.9	24.0	1178	1173
2-PENTANOL	48.7	15.4	1085	1073
3-PENTANOL	45.8	15.2	1073	1070
2-METHYL-1-BUTANOL	79.5	23.9	1177	1172
2-METHYL-2-BUTANOL	26.9	9.5	975	965
3-METHYL-2-BUTANOL	42.0	13.8	1057	1048
2,2-DIMETHYL-1-PROPANOL	45.7	14.9	1073	1065
HEXANOL	177	45.9	1331	1321
2-HEXANOL	84.3	25.1	1188	1182
3-HEXANOL	75.7	22.7	1168	1160
2-METHYL-1-PENTANOL	136	36.5	1281	1265
3-METHYL-1-PENTANOL	157	41.4	1309	1297
4-METHYL-1-PENTANOL	147	38.8	1295	1282
2-METHYL-2-PENTANOL	44.0	14.3	1066	1056
3-METHYL-2-PENTANOL	74.0	22.7	1164	1160
4-METHYL-2-PENTANOL	62.7	19.4	1133	1124
2-METHYL-3-PENTANOL	60.7	19.1	1126	1121
3-METHYL-3-PENTANOL	48.6	15.9	1085	1080
2-ETHYL-1-BUTANOL	138	38.1	1283	1278
2,2-DIMETHYL-1-BUTANOL	97.2	28.7	1216	1213
2,3-DIMETHYL-2-BUTANOL	42.5	14.4	1059	1058
3,3-DIMETHYL-2-BUTANOL	51.2	16.9	1094	1093
HEPTANOL	304	74.1	1435	1430
2-HEPTANOL		38.3		1279
3-HEPTANOL	127	34.6	1267	1256
4-HEPTANOL	121	32.9	1258	1244
2,2-DIMETHYL-1-PENTANOL	156	41.4	1307	1297
2,4-DIMETHYL-3-PENTANOL	74.4	22.9	1165	1162
3-ETHYL-3-PENTANOL	85.4	25.2	1191	1183
OCTANOL	534	112	1545	1526
2-OCTANOL	252	62.9	1399	1393
2-ETHYL-1-HEXANOL	379	84.4	1478	1460
2-ETHYL-4-METHYL-1-PENTANOL	274	67.8	1415	1410
NONANOL	906	181	1648	1638
CYCLOPENTANOL	140	38.9	1287	1283
CYCLOHEXANOL	238	64.1	1388	1397
2-METHYLCYCLOHEXANOL	255	68.7	1402	1413
2-PROPEN-1-OL	46.0	14.6	1074	1061
2-PROPYN-1-OL	155	39.8	1306	1288
2-BUTEN-1-OL	84.4	25.0	1189	1182
3-BUTEN-1-OL	66.1	20.5	1143	1137
3-BUTEN-2-OL	37.3	12.3	1035	1022
2-METHYL-2-PROPEN-1-OL	76.9	23.0	1171	1163
3-PENTEN-1-OL	117	33.8	1252	1251
1-PENTEN-3-OL	60.9	18.6	1127	1116
1-PENTEN-4-OL	55.2	17.6	1109	1103
2-METHYL-3-BUTEN-2-OL	30.7	10.3	998	982
2-METHYL-3-BUTYN-2-OL	68.4	19.2	1149	1122
3-METHYL-1-PENTYN-3-OL	110	30.0	1241	1223
2-ETHYL-2-HEXEN-1-OL		108		1518
ETHYLENE GLYCOL		147		1588
1,2-PROPANEDIOL		121		1544
1,3-PROPANEDIOL		270		1731
1,2-BUTANEDIOL		177		1633
1,3-BUTANEDIOL		228		1692
1,4-BUTANEDIOL		469		1861
D,L-2,3-BUTANEDIOL		100		1500
MESO-2,3-BUTANEDIOL		112		1526
2-METHYL-1,2-PROPANEDIOL		94.1		1485
1,5-PENTANEDIOL		742		1970
2,4-PENTANEDIOL		181		1637
2,2-DI ME-1,3-PROPANEDIOL		291		1749
1,2-HEXANEDIOL		143		1582
1,6-HEXANEDIOL		1154		2051
2-METHYL-1,3-PENTANEDIOL		384		1814
2-METHYL-2,4-PENTANEDIOL		143		1583
3-METHYL-2,4-PENTANEDIOL		254		1717
3-METHYL-1,5-PENTANEDIOL		966		2022
2,3-DIMETHYL-2,3-BUTANEDIOL		81.3		1452
2,4-HEPTANEDIOL		358		1797
1,2-OCTANEDIOL		987		2025
2-BUTEN-1,4-DIOL		774		1983
DIETHYLENE GLYCOL		595		1917
FORMALDEHYDE	3.2	1.9	601	630
ACETALDEHYDE	5.2	2.6	686	690
PROPIONALDEHYDE	9.3	4.2	788	784
BUTYRALDEHYDE	15.9	6.6	882	882
ISOBUTYRALDEHYDE	11.6	5.3	827	832
VALERALDEHYDE	28.4	11.2	984	1002
ISOVALERALDEHYDE	20.4	8.4	926	937
2-METHYLBUTYRALDEHYDE	20.3	8.4	925	936
2,2-DIMETHYLPROPIONALDEHYDE	11.2	5.0	821	822
HEXANAL	49.3	18.0	1087	1108
HEPTANAL	83.9	28.0	1188	1207
2-ETHYLHEXANAL	88.1	29.1	1187	1216
ACROLEIN	13.0	5.7	846	849
METHACROLEIN	16.0	7.0	884	895
CROTONALDEHYDE	40.0	14.8	1048	1064
2-ETHYL-2-BUTENAL	74.4	25.8	1165	1189
2-ETHYL-2-HEXENAL	158	49.1	1309	1336
2,4-HEXADIENAL	254	72.8	1401	1426
ACETONE	10.9	4.9	815	819
2-BUTANONE	18.0	7.4	904	908
2-PENTANONE	28.2	10.7	982	992
3-PENTANONE	28.0	10.5	982	987
3-METHYL-2-BUTANONE	22.0	8.8	939	947
2-HEXANONE	49.3	17.3	1087	1095
3-HEXANONE	42.2	15.0	1058	1067
3-METHYL-2-PENTANONE	35.7	14.2	1026	1054
4-METHYL-2-PENTANONE	33.0	12.7	1012	1030
3,3-DIMETHYL-2-BUTANONE	25.1	10.3	962	982
2-HEPTANONE	84.1	26.1	1188	1192
3-HEPTANONE	72.3	24.1	1159	1174
4-HEPTANONE	63.0	21.8	1134	1151
4,4-DIMETHYL-2-PENTANONE	36.0	14.1	1028	1052
2,4-DIMETHYL-3-PENTANONE	32.9	12.7	1011	1029
2-OCTANONE	146	42.7	1295	1304
2-NONANONE	240	70.7	1390	1420
5-NONANONE	185	54.6	1340	1360
CYCLOPENTANONE	92.8	32.0	1207	1239
CYCLOHEXANONE	166	54.7	1319	1361
3-BUTEN-2-ONE	23.1	9.3	948	959
5-HEXEN-2-ONE	62.3	21.4	1131	1147
3-METHYL-3-BUTEN-2-ONE	30.6	11.9	997	1014
4-METHYL-3-PENTEN-2-ONE	66.2	23.0	1143	1164
2,3-BUTANEDIONE	24.6	9.4	959	963
2,3-PENTANEDIONE	38.9	13.7	1042	1046
2,4-PENTANEDIONE	103	36.4	1228	1259
METHYL FORMATE	7.3	3.2	745	734
ETHYL FORMATE	11.0	4.8	817	810
PROPYL FORMATE	19.5	7.8	918	915
ISOPROPYL FORMATE	13.1	5.4	848	837
BUTYL FORMATE	33.5	12.2	1014	1021
ISOBUTYL FORMATE	25.3	9.6	964	967
S-BUTYL FORMATE	23.1	9.1	948	956
PENTYL FORMATE	58.3		1119	
2-PENTYL FORMATE	37.6	14.1	1036	1053
3-PENTYL FORMATE	39.7	14.2	1046	1054
HEXYL FORMATE	102	31.3	1226	1233
ALLYL FORMATE	24.9	9.6	961	966
ETHYLENE DIFORMATE	399		1488	
1,3-BUTYLENE DIFORMATE	630	150	1576	1594
METHYL ACETATE	11.4	4.8	824	813
ETHYL ACETATE	15.6	6.3	879	871
PROPYL ACETATE	25.7	9.7	967	969
ISOPROPYL ACETATE	16.5	6.6	889	882
BUTYL ACETATE	44.1	15.0	1066	1067
ISOBUTYL ACETATE	31.9	11.5	1005	1007
S-BUTYL ACETATE	27.7	10.3	980	982
T-BUTYL ACETATE	17.4	6.8	898	888
PENTYL ACETATE	79.3	24.8	1177	1180
ISOPENTYL ACETATE	61.1	19.6	1128	1128
2-PENTYL ACETATE	44.5	15.3	1068	1071
3-PENTYL ACETATE	44.1	14.9	1066	1066
2-METHYL-2-BUTYL ACETATE	32.4	12.0	1008	1017
HEXYL ACETATE	136	40.5	1281	1292
4-METHYL-2-PENTYL ACETATE	53.1	17.6	1101	1102
2-ETHYL-1-BUTYL ACETATE	100	29.8	1223	1222
HEPTYL ACETATE	232	60.8	1383	1385
2-ETHYL-1-HEXYL ACETATE	247	65.4	1396	1405
CYCLOHEXYL ACETATE	211	64.2	1365	1397
VINYL ACETATE	16.0	6.5	883	878
ALLYL ACETATE	33.6	12.0	1015	1016
ISOPROPENYL ACETATE	27.0	10.0	976	977
1-ACETOXY-2-PROPYNE	91.0	26.1	1203	1192
METHYLENE DIACETATE	357	69.3	1466	1415
ETHYLIDENE DIACETATE	210	55.6	1364	1364
ETHYLENE DIACETATE	506	120	1534	1542
METHYL PROPIONATE	17.6	7.0	900	896
ETHYL PROPIONATE	23.4	9.0	950	952
PROPYL PROPIONATE	38.0	13.1	1038	1036
ISOPROPYL PROPIONATE	23.9	9.0	954	953

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Table 31 (cont.)

	V_g		I_x	
	120°	160°	120°	160
BUTYL PROPIONATE	66.7	21.5	1144	1149
ISOBUTYL PROPIONATE	48.1	15.8	1083	1079
PENTYL PROPIONATE	114	35.5	1246	1252
ISOPENTYL PROPIONATE	88.6	29.1	1156	1216
2-PENTYL PROPIONATE	65.5	19.0	1141	1120
2-ETHYL-1-HEXYL PROPIONATE	345	80.7	1460	1450
ALLYL PROPIONATE	50.3	16.6	1091	1090
METHYL BUTYRATE	27.8	10.4	961	985
ETHYL BUTYRATE	36.6	12.8	1031	1032
PROPYL BUTYRATE	61.5	19.6	1129	1127
ISOPROPYL BUTYRATE	36.9	12.6	1033	1028
BUTYL BUTYRATE	103	30.7	1228	1225
ISOBUTYL BUTYRATE	74.9	23.8	1156	1171
PENTYL BUTYRATE	171	47.0	1325	1325
ISOPENTYL BUTYRATE	134	38.4	1277	1280
2-PENTYL BUTYRATE	101	29.4	1224	1219
VINYL BUTYRATE	35.5	12.3	1026	1031
METHYL ISOBUTYRATE	19.6	7.8	919	920
BUTYL ISOBUTYRATE	70.0	22.3	1153	1156
ISOBUTYL ISOBUTYRATE	50.4	16.7	1091	1092
METHYL ACRYLATE	21.1	8.4	932	938
ETHYL ACRYLATE	28.4	10.8	984	994
PROPYL ACRYLATE	46.5	16.2	1076	1065
BUTYL ACRYLATE	80.5	25.7	1180	1189
ISOBUTYL ACRYLATE		18.0		1107
2-ETHYL-1-HEXYL ACRYLATE		97.5		1494
ALLYL ACRYLATE	60.5	20.4	1126	1136
METHYL METHACRYLATE	31.2	11.5	1001	1008
METHYLAL	7.1	3.3	745	735
ETHYL METHYL FORMAL	10.2	4.6	804	803
ISOPROPYL METHYL FORMAL	12.7	5.3	836	834
DIETHYL FORMAL	13.8	5.9	857	857
PROPYL ETHYL FORMAL	22.5	8.8	943	948
ISOPROPYL ETHYL FORMAL	16.5	6.6	888	884
S-BUTYL ETHYL FORMAL	28.4	10.8	984	992
DIPROPYL FORMAL	35.6	12.8	1026	1031
S-BUTYL PROPYL FORMAL	45.0	15.8	1070	1078
DIISOPROPYL FORMAL	19.5	7.5	918	913
DIBUTYL FORMAL	95.3	30.6	1212	1226
DIISOBUTYL FORMAL	53.2	17.3	1102	1099
DI S-BUTYL FORMAL	61.5	19.0	1129	1120
ETHYLENE GLYCOL FORMAL	26.1	10.4	969	984
1,2-PROPYLENE GLYCOL FORMAL	26.5	10.6	972	989
1,3-PROPYLENE GLYCOL FORMAL	52.1	19.2	1098	1123
1,3-BUTYLENE GLYCOL FORMAL	53.6	19.7	1103	1128
2,3-BUTYLENE GLYCOL FORMAL	34.5	13.1	1020	1037
1,4-BUTYLENE GLYCOL FORMAL	64.0	24.3	1137	1176
NEOPENTYL GLYCOL FORMAL	57.9	20.8	1118	1140
6-METHYL-2,4,7-TRIOXAOCTANE	74.4	24.3	1165	1176
DIMETHYL ACETAL	10.0	4.5	800	800
DIETHYL ACETAL	16.0	6.5	884	879
DIPROPYL ACETAL	37.5	12.8	1035	1032
DIISOBUTYL ACETAL	46.2	15.4	1075	1072
ETHYLENE GLYCOL ACETAL	24.5	9.6	958	966
1,3-BUTYLENE GLYCOL ACETAL	43.3	15.4	1063	1072
DIMETHYL PROPYLAL	15.7	6.6	880	884
DIETHYL PROPYLAL	23.2	8.8	948	947
DIMETHYL BUTYRAL	25.5	9.8	965	972
1,3-BUTYLENE GLYCOL BUTYRAL	102	31.1	1226	1232
DIMETHYL ISOBUTYRAL	18.7	7.6	910	916
ACROLEIN DIETHYL ACETAL	29.7	11.0	992	997
DIBUTYL CROTANAL	346	76.9	1460	1439
4,4-DIMETHOXY-2-BUTANONE	243	64.6	1392	1399
2,2-DIMETHOXYPROPANE	11.9	5.3	831	834
2,2-DIETHOXYPROPANE	16.1	6.4	884	875
2,2-DIALLYLOXYPROPANE	71.9	22.9	1158	1163
2-ET-2-ME-1,3-DIOXOLANE	41.8	15.1	1056	1068
METHYL ETHER	1.7	1.1	493	524
PROPYL METHYL ETHER	4.1	2.0	644	644
BUTYL METHYL ETHER	7.3	3.6	746	755
ISOBUTYL METHYL ETHER	5.2	2.5	685	683
T-BUTYL METHYL ETHER	5.1	2.6	684	688
ETHYL ETHER	3.5	1.7	620	610
BUTYL ETHYL ETHER	9.6	4.3	794	788
T-BUTYL ETHYL ETHER	5.6	2.6	699	688
ALLYL ETHYL ETHER	8.4	3.8	771	767
PROPYL ETHER	8.5	3.8	773	766
ISOPROPYL PROPYL ETHER	6.0	2.9	712	714
ISOPROPYL ETHER	4.3	2.1	652	649
T-BUTYL ISOPROPYL ETHER	6.3	3.0	720	717
BUTYL ETHER	25.6	9.7	966	969
PENTYL ETHER	74.4	23.2	1165	1165
ISOPENTYL ETHER	43.4	15.0	1063	1067
HEXYL ETHER	227	55.4	1379	1363
2-ETHYL-1-BUTYL ETHER	101	28.6	1224	1212
ETHYL VINYL ETHER	4.9	2.3	677	668

	V_g		I_x	
	120°	160°	120°	160
BUTYL VINYL ETHER	13.9	6.0	858	862
ISOBUTYL VINYL ETHER	10.0	4.3	800	784
2-ETHYL-1-HEXYL VINYL ETHER	80.3	23.3	1179	1165
ET GLYCOL DIMETHYL ETHER	19.5	7.8	918	920
ET GLYCOL DIBUTYL ETHER	204	51.8	1359	1348
ETHYLENE OXIDE	5.6	2.9	700	712
PROPYLENE OXIDE	8.1	4.2	763	783
1,3-PROPYLENE OXIDE	12.9	5.7	845	852
1,2-BUTYLENE OXIDE	13.2	5.9	849	856
1,3-BUTYLENE OXIDE	12.7	5.9	843	852
TRANS-2,3-BUTYLENE OXIDE	9.3	4.2	787	785
CIS-2,3-BUTYLENE OXIDE	12.0	5.3	833	835
TETRAHYDROFURAN	16.0	7.0	883	895
2-ME-1,2-PROPYLENE OXIDE	8.4	3.9	771	769
2-METHYLTETRAHYDROFURAN	16.4	7.2	888	901
FURAN	9.5	4.2	791	784
2-METHYLFURAN	14.8	6.3	869	873
2,5-DIMETHYLTETRAHYDROFURAN	15.2	6.5	874	881
4,5-DIHYDRO-2-METHYLFURAN	19.7	8.3	919	934
3,4-DIHYDROPYRAN	25.1	10.3	963	987
TETRAHYDROPYRAN	23.0	9.5	947	967
ETHANE	.3	.2	200	200
BUTANE	1.0	.6	400	400
HEXANE	3.2	1.5	600	600
2,3-DIMETHYLBUTANE	2.7	1.6	574	598
OCTANE	9.9	4.5	800	800
DECANE	31.0	11.1	1000	1000
DODECANE	89.4	27.0	1200	1200
TETRADECANE	253	64.9	1400	1400
HEXADECANE	710	154	1600	1600
OCTADECANE	1960	362	1800	1800
CYCLOHEXANE	7.8	3.8	756	765
1-PENTENE	2.3		545	
BENZENE	24.9	10.2	961	979
TOLUENE	42.8	15.9	1061	1079
O-XYLENE	96.0	30.1	1213	1224
M-XYLENE	77.6	25.3	1173	1184
P-XYLENE	75.0	24.8	1166	1180
ETHYLBENZENE	69.6	24.3	1152	1175
O-DIETHYLBENZENE	204	57.5	1359	1372
M-DIETHYLBENZENE	177	49.8	1331	1339
P-DIETHYLBENZENE	187	52.9	1341	1353
METHYLENE CHLORIDE	19.0	7.6	914	915
ETHYLENE CHLORIDE	42.8	15.6	1061	1075
ALLYL CHLORIDE	11.0		818	
CARBON TETRACHLORIDE	17.1	7.4	895	910
CHLOROFORM	32.0	11.6	1005	1010
2-CHLOROETHANOL	198	56.2	1353	1367
3-HYDROXY-2-BUTANONE	140	40.7	1286	1293
4-HYDROXY-2-BUTANONE	470	114	1520	1530
1-HYDROXY-2-ME-3-BUTANONE	641	146	1580	1587
2-HYDROXY-2-ME-3-BUTANONE	106	32.8	1233	1244
4-HYDROXY-4-ME-2-PENTANONE	202	57.0	1357	1370
3-METHOXYBUTANAL	72.7	23.6	1160	1169
4-ACETOXYTETRAHYDROPYRAN	466	111	1519	1524
2-METHOXYETHANOL	72.1	23.6	1159	1169
2-ETHOXYETHANOL	91.0	29.2	1203	1217
2-BUTOXYETHANOL	243	62.9	1392	1393
2-ALLYLOXYETHANOL	226	59.3	1378	1379
2-METHOXY-1-PROPANOL	84.2	25.6	1188	1187
2-ETHOXY-1-PROPANOL	95.6	28.8	1213	1214
3-ETHOXY-1-PROPANOL	204	53.1	1358	1354
1-METHOXY-2-PROPANOL	57.2	19.0	1115	1120
1-PROPOXY-2-PROPANOL	104	31.5	1229	1234
3-METHOXY-1-BUTANOL	200	53.2	1355	1354
1-ETHOXY-3-PENTANOL	233	61.3	1384	1387
4-METHOXY-4-ME-2-PENTANOL	159	47.9	1310	1330
2-METHOXYETHYL VINYL ETHER	36.8	12.8	1032	1031
BIS(2-ETHOXYETHYL) ETHER	256	63.0	1402	1393
3-METHOXY-1-BUTYL ACETATE	182	49.6	1337	1338
2-METHOXYETHYL ACETATE	107	30.7	1235	1229
2-ETHOXYETHYL ACETATE	135	37.4	1280	1274
ACETONYL ACETATE	314	75.3	1442	1434
3-METHOXY-1-BUTYL ACRYLATE	183	49.6	1338	1338
1,1,3-TRIMETHOXYBUTANE	98.2	29.8	1218	1222
METHOXYMETHYLAL	34.1	12.7	1018	1029
DIMETHOXYMETHYLAL	142	42.3	1298	1302
TRIMETHOXYMETHYLAL	561	134	1554	1568
1,4-DI[illegible]	45.7	17.0	1073	1094
TRIOXANE	74.7	25.5	1166	1186
1,3,5-TRIOXEPANE	114	37.0	1247	1271
PARALDEHYDE	45.6	15.0	1073	1067
WATER	29.4	9.6	990	967

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Table 31 (cont.)

	V_g		I_x			V_g		I_x	
	120°	160°	120°	160°		120°	160°	120°	160
ETHANE	.3	.2	200	200	S-BUTYL FORMATE	23.1	9.1	946	[illegible]
BUTANE	1.0	.6	400	400	3-BUTEN-2-ONE	[illegible]	9.3	944	[illegible]
METHYL ETHER	1.7	1.1	493	524	2,3-BUTANEDIONE	24.6	9.4	[illegible]	[illegible]
1-PENTENE	2.3		545		2-METHYL-2-BUTANOL	[illegible]	[illegible]	975	[illegible]
2,3-DIMETHYLBUTANE	2.7	1.6	574	598	ETHYLENE GLYCOL ACETAL	24.5	9.6	958	965
HEXANE	3.2	1.6	600	600	ALLYL FORMATE	24.9	9.6	961	966
ETHYL ETHER	3.5	1.7	620	610	TETRAHYDROPYRAN	[illegible]	9.6	947	967
FORMALDEHYDE	3.2	1.9	601	630	WATER	29.4	9.6	950	967
PROPYL METHYL ETHER	4.1	2.0	644	644	ISOBUTYL FORMATE	25.3	9.6	964	967
ISOPROPYL ETHER	4.3	2.1	652	649	BUTYL ETHER	25.6	9.7	966	969
ETHYL VINYL ETHER	4.9	2.3	677	668	PROPYL ACETATE	25.7	9.7	967	969
ISOBUTYL METHYL ETHER	5.2	2.5	685	683	DIMETHYL BUTYRAL	25.5	9.6	965	972
T-BUTYL METHYL ETHER	5.1	2.6	684	688	S-BUTANOL	28.6	10.0	966	975
T-BUTYL ETHYL ETHER	5.6	2.6	699	688	ISOPROPENYL ACETATE	[illegible]	10.0	976	977
ACETALDEHYDE	5.2	2.6	686	690	BENZENE	24.9	10.2	961	979
ETHYLENE OXIDE	5.6	2.9	700	712	3,4-DIHYDROPYRAN	25.1	10.3	963	[illegible]
ISOPROPYL PROPYL ETHER	6.0	2.9	712	714	2-METHYL-3-BUTEN-2-OL	30.7	10.3	998	982
T-BUTYL ISOPROPYL ETHER	6.3	3.0	720	717	3,3-DIMETHYL-2-BUTANONE	25.1	10.3	967	982
METHYL FORMATE	7.3	3.2	745	734	S-BUTYL ACETATE	27.7	10.3	980	[illegible]
METHYLAL	7.1	3.3	740	735	ETHYLENE GLYCOL FORMAL	28.1	10.4	969	984
BUTYL METHYL ETHER	7.3	3.6	746	755	PROPANOL	31.0	10.5	1000	986
CYCLOHEXANE	7.8	3.8	756	765	METHYL BUTYRATE	27.8	10.4	981	986
PROPYL ETHER	8.5	3.8	773	766	3-PENTANONE	28.0	10.5	982	987
ALLYL ETHYL ETHER	8.4	3.8	771	767	1,2-PROPYLENE GLYCOL FORMAL	26.5	10.6	972	989
2-ME-1,2-PROPYLENE OXIDE	8.4	3.9	771	769	S-BUTYL ETHYL FORMAL	28.4	10.8	984	992
PROPYLENE OXIDE	8.1	4.2	763	783	2-PENTANONE	28.2	10.7	983	992
PROPIONALDEHYDE	9.3	4.2	788	784	ETHYL ACRYLATE	28.4	10.8	984	994
TRANS-2,3-BUTYLENE OXIDE	9.3	4.2	787	785	ACROLEIN DIETHYL ACETAL	29.7	11.0	992	997
FURAN	9.5	4.2	791	786	DECANE	31.0	11.1	1000	1000
BUTYL ETHYL ETHER	9.6	4.3	794	788	VALERALDEHYDE	28.4	11.2	984	1002
ISOBUTYL VINYL ETHER	10.0	4.3	800	788	ISOBUTYL ACETATE	31.9	11.5	1005	1007
DIMETHYL ACETAL	10.0	4.5	800	800	METHYL METHACRYLATE	31.2	11.5	1001	1008
OCTANE	9.9	4.5	800	800	CHLOROFORM	32.0	11.5	1006	1010
ETHYL METHYL FORMAL	10.2	4.5	804	803	3-METHYL-3-BUTEN-2-ONE	30.5	11.7	997	1014
ETHYL FORMATE	11.0	4.6	817	810	ALLYL ACETATE	33.6	12.0	1015	1016
METHYL ACETATE	11.4	4.6	824	813	2-METHYL-2-BUTYL ACETATE	32.4	12.0	1008	1017
ALLYL CHLORIDE	11.0		818		BUTYL FORMATE	33.5	12.2	1014	1021
ACETONE	10.9	4.9	815	819	3-BUTEN-2-OL	37.3	12.3	1035	1022
2,2-DIMETHYLPROPIONALDEHYDE	11.2	5.0	821	822	ISOPROPYL BUTYRATE	36.9	12.6	1033	1028
T-BUTANOL	13.8	5.2	857	830	METHOXYMETHYLAL	34.1	12.7	1018	1024
ISOBUTYRALDEHYDE	11.6	5.3	827	832	2,4-DIMETHYL-3-PENTANONE	32.9	12.7	1011	1029
2,2-DIMETHOXYPROPANE	11.9	5.3	831	834	4-METHYL-2-PENTANONE	33.0	12.7	1012	1030
CIS-2,3-BUTYLENE OXIDE	12.0	5.3	833	835	DIPROPYL FORMAL	35.6	12.8	1026	1031
ISOPROPYL METHYL FORMAL	12.2	5.3	836	836	2-METHOXYETHYL VINYL ETHER	36.6	12.6	1032	1031
ISOPROPYL FORMATE	13.1	5.4	848	837	VINYL BUTYRATE	35.5	12.8	1026	1031
METHANOL	14.2	5.5	862	842	DIPROPYL ACETAL	37.5	12.8	1035	1032
ACROLEIN	13.0	5.7	846	849	ETHYL BUTYRATE	36.6	12.6	1031	1032
1,3-PROPYLENE OXIDE	12.9	5.7	845	852	PROPYL PROPIONATE	38.0	13.1	1038	1036
1,3-BUTYLENE OXIDE	12.7	5.8	843	852	2,3-BUTYLENE GLYCOL FORMAL	34.5	13.1	1020	1037
1,2-BUTYLENE OXIDE	13.2	5.9	849	856	ISOBUTANOL	41.5	13.6	1055	1045
DIETHYL FORMAL	13.8	5.9	857	857	2,3-PENTANEDIONE	38.9	13.7	1042	1046
BUTYL VINYL ETHER	13.9	6.0	858	862	3-METHYL-2-BUTANOL	42.0	13.8	1057	1048
ISOPROPANOL	16.0	6.0	883	862	4,4-DIMETHYL-2-PENTANONE	36.0	14.1	1028	1052
ETHANOL	16.9	6.2	893	869	2-PENTYL FORMATE	37.6	14.1	1036	1053
ETHYL ACETATE	15.6	6.3	879	871	3-METHYL-2-PENTANONE	35.7	14.2	1026	1054
2-METHYLFURAN	14.8	6.3	869	873	3-PENTYL FORMATE	39.7	[illegible]	1046	1054
2,2-DIETHOXYPROPANE	16.1	6.4	884	875	2-METHYL-2-PENTANOL	44.0	14.3	1066	1056
VINYL ACETATE	16.0	6.5	883	878	2,3-DIMETHYL-2-BUTANOL	42.5	14.4	1059	1055
DIETHYL ACETAL	16.0	6.5	884	879	2-PROPEN-1-OL	46.0	14.6	1074	1061
2,5-DIMETHYLTETRAHYDROFURAN	15.2	6.5	874	881	CROTONALDEHYDE	40.0	14.8	1048	1064
BUTYRALDEHYDE	15.9	6.6	882	882	2,2-DIMETHYL-1-PROPANOL	45.7	14.9	1073	1065
ISOPROPYL ACETATE	16.5	6.6	889	882	3-PENTYL ACETATE	44.1	14.9	1066	1066
ISOPROPYL ETHYL FORMAL	16.5	6.6	888	884	ISOPENTYL ETHER	43.4	15.0	1063	1067
DIMETHYL PROPYLAL	15.7	6.6	880	884	PARALDEHYDE	45.6	15.0	1073	1067
T-BUTYL ACETATE	17.4	6.8	898	885	3-HEXANONE	42.2	15.0	1058	1067
METHACROLEIN	16.0	7.0	884	896	BUTYL ACETATE	44.1	15.0	1066	1067
METHYL PROPIONATE	17.6	7.0	900	896	2-ET-2-ME-1,3-DIOXOLANE	41.8	15.1	1056	1068
TETRAHYDROFURAN	16.0	7.0	883	898	3-PENTANOL	45.8	15.2	1073	1070
2-METHYLTETRAHYDROFURAN	16.4	7.2	886	901	2-PENTYL ACETATE	44.5	15.3	1068	1071
2-BUTANONE	18.0	7.4	904	908	DIISOBUTYL ACETAL	46.2	15.4	1075	1072
CARBON TETRACHLORIDE	17.1	7.4	895	910	1,3-BUTYLENE GLYCOL ACETAL	43.3	15.4	1063	1072
DIISOPROPYL FORMAL	19.5	7.5	918	913	2-PENTANOL	48.7	15.4	1085	1073
METHYLENE CHLORIDE	19.0	7.6	914	915	ETHYLENE CHLORIDE	42.8	15.6	1061	1075
DIMETHYL ISOBUTYRAL	18.7	7.6	910	916	S-BUTYL PROPYL FORMAL	45.0	15.8	1070	1076
PROPYL FORMATE	19.5	7.8	918	919	TOLUENE	42.8	15.7	1061	1074
ET GLYCOL DIMETHYL ETHER	19.5	7.8	918	920	ISOBUTYL PROPIONATE	48.1	15.8	1083	1079
METHYL ISOBUTYRATE	19.6	7.8	919	920	3-METHYL-3-PENTANOL	48.6	15.9	1085	1080
4,5-DIHYDRO-2-METHYLFURAN	19.7	8.3	919	934	PROPYL ACRYLATE	46.5	16.2	1076	1081
2-METHYLBUTYRALDEHYDE	20.3	8.4	925	936	ALLYL PROPIONATE	50.3	16.6	1091	1090
ISOVALERALDEHYDE	20.4	8.4	926	937	ISOBUTYL ISOBUTYRATE	50.4	16.7	1091	1092
METHYL ACRYLATE	21.1	8.4	932	938	3,3-DIMETHYL-2-BUTANOL	51.2	16.9	1094	1093
DIETHYL PROPYLAL	23.2	8.8	948	947	1,4-DIOXANE	45.7	17.3	1073	1094
3-METHYL-2-BUTANONE	22.0	8.8	939	947	DIISOBUTYL FORMAL	53.2	17.4	1102	1099
PROPYL ETHYL FORMAL	22.5	8.8	943	948	2-HEXANONE	49.3	17.3	1087	1099
ETHYL PROPIONATE	23.4	9.0	950	952	BUTANOL	56.0	17.5	1111	1101
ISOPROPYL PROPIONATE	23.9	9.0	954	953	4-METHYL-2-PENTYL ACETATE	53.1	17.6	1101	1102

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Table 31 (cont.)

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	V_g		I_x	
	120°	160°	120°	160°
1-PENTEN-4-OL	55.2	17.6	1109	1103
ISOBUTYL ACRYLATE		18.0		1107
HEXANAL	49.3	18.0	1087	1108
1-PENTEN-3-OL	60.9	18.6	1127	1116
DI S-BUTYL FORMAL	61.5	19.0	1129	1120
1-METHOXY-2-PROPANOL	57.2	19.0	1115	1120
PENTYL FORMATE	58.3		1119	
2-PENTYL PROPIONATE	65.5	19.0	1141	1120
2-METHYL-3-PENTANOL	66.7	19.1	1126	1121
2-METHYL-3-BUTYN-2-OL	68.4	19.2	1149	1122
1,3-PROPYLENE GLYCOL FORMAL	52.1	19.2	1098	1123
4-METHYL-2-PENTANOL	62.7	19.4	1133	1124
PROPYL BUTYRATE	61.5	19.6	1129	1127
1,3-BUTYLENE GLYCOL FORMAL	53.6	19.7	1103	1128
ISOPENTYL ACETATE	61.1	19.6	1128	1128
ALLYL ACRYLATE	60.5	20.4	1126	1136
3-BUTEN-1-OL	66.1	20.5	1143	1137
NEOPENTYL GLYCOL FORMAL	57.9	20.8	1118	1140
5-HEXEN-2-ONE	62.3	21.4	1131	1147
BUTYL PROPIONATE	66.7	21.5	1144	1148
4-HEPTANONE	63.0	21.8	1134	1151
BUTYL ISOBUTYRATE	70.0	22.3	1153	1156
3-HEXANOL	75.7	22.7	1168	1160
3-METHYL-2-PENTANOL	74.0	22.7	1164	1160
2,4-DIMETHYL-3-PENTANOL	74.4	22.9	1165	1162
2,2-DIALLYLOXYPROPANE	71.9	22.9	1158	1163
2-METHYL-2-PROPEN-1-OL	76.9	23.0	1171	1163
4-METHYL-3-PENTEN-2-ONE	66.2	23.0	1143	1164
PENTYL ETHER	74.4	23.2	1165	1165
2-ETHYL-1-HEXYL VINYL ETHER	80.3	23.2	1179	1165
3-METHOXYBUTANAL	72.7	23.6	1160	1169
2-METHOXYETHANOL	72.1	23.6	1159	1169
ISOBUTYL BUTYRATE	74.9	23.6	1166	1171
2-METHYL-1-BUTANOL	79.5	23.9	1177	1172
ISOPENTANOL	79.4	24.0	1178	1173
3-HEPTANONE	72.9	24.1	1159	1174
1,4-BUTYLENE GLYCOL FORMAL	54.0	24.3	1137	1176
6-METHYL-2,4,7-TRIOXAOCTANE	74.4	24.3	1165	1176
ETHYLBENZENE	67.6	24.3	1152	1176
P-XYLENE	75.0	24.6	1166	1180
PENTYL ACETATE	79.3	24.8	1177	1180
2-HEXANOL	84.3	25.1	1186	1182
2-BUTEN-1-OL	84.4	25.0	1189	1182
3-ETHYL-3-PENTANOL	85.4	25.2	1191	1183
M-XYLENE	77.6	25.3	1173	1184
TRIOXANE	74.7	25.5	1166	1186
2-METHOXY-1-PROPANOL	84.2	25.6	1188	1187
2-ETHYL-2-BUTENAL	74.4	25.8	1165	1189
BUTYL ACRYLATE	80.5	25.7	1180	1189
2-HEPTANONE	84.1	26.1	1188	1192
1-ACETOXY-2-PROPYNE	91.0	26.1	1203	1192
DODECANE	89.4	27.0	1200	1200
CYCLOPROPYL CARBINOL	91.3	27.3	1203	1201
HEPTANAL	83.9	28.0	1188	1207
2-ETHYL-1-BUTYL ETHER	101	29.6	1224	1212
2,2-DIMETHYL-1-BUTANOL	97.2	28.7	1216	1213
2-ETHOXY-1-PROPANOL	95.6	28.8	1213	1214
PENTANOL	105	28.9	1223	1215
2-ETHYLHEXANAL	88.1	29.1	1197	1216
ISOPENTYL PROPIONATE	88.8	29.1	1198	1216
2-ETHOXYETHANOL	91.0	29.2	1203	1217
2-PENTYL BUTYRATE	10[illegible]	29.4	1224	1219
1,1,3-TRIMETHOXYBUTANE	98.2	29.8	1218	1222
2-ETHYL-1-BUTYL ACETATE	100	29.6	1223	1222
3-METHYL-1-PENTYN-3-OL	110	30.0	1241	1223
O-XYLENE	96.0	30.1	1213	1224
DIBUTYL FORMAL	95.3	30.6	1212	1226
2-METHOXYETHYL ACETATE	107	30.7	1235	1229
BUTYL BUTYRATE	103	30.7	1228	1229
1,3-BUTYLENE GLYCOL BUTYRAL	102	31.1	1226	1232
HEXYL FORMATE	102	31.3	1226	1233
1-PROPOXY-2-PROPANOL	104	31.5	1229	1234
CYCLOPENTANONE	92.8	32.0	1207	1238
2-HYDROXY-2-ME-3-BUTANONE	106	32.8	1233	1244
4-HEPTANOL	121	32.9	1258	1244
3-PENTEN-1-OL	113	33.4	1252	1251
3-HEPTANOL	127	34.6	1267	1256
PENTYL PROPIONATE	114	35.5	1248	1262
2-METHYL-1-PENTANOL	136	36.[illegible]	1281	1268
2,4-PENTANEDIONE	133	36.4	1228	1268
1,1,3-TRIMETHOXYPROPANE	114	37.0	1247	1271
2-ETHOXYETHYL ACETATE	139	37.6	1280	1274
2-ETHYL-1-BUTANOL	138	38.1	1283	1276
2-HEPTANOL		38.3		1279
ISOPENTYL BUTYRATE	134	38.4	1277	1280
4-METHYL-1-PENTANOL	147	38.8	1295	1282
CYCLOPENTANOL	140	38.9	1287	1283
2-PROPYN-1-OL	155	39.8	1306	1289
HEXYL ACETATE	136	40.5	1281	1292
3-HYDROXY-2-BUTANONE	140	40.7	1286	1293
3-METHYL-1-PENTANOL	157	41.4	1309	1297
2,2-DIMETHYL-1-PENTANOL	156	41.4	1307	1297
DIMETHOXYMETHYLAL	142	42.3	1288	1302
2-OCTANONE	146	42.7	1295	1304
HEXANOL	177	45.9	1331	1321
PENTYL BUTYRATE	171	47.0	1325	1326
4-METHOXY-4-ME-2-PENTANOL	159	47.9	1310	1330
2-ETHYL-2-HEXENAL	158	49.1	1309	1336
3-METHOXY-1-BUTYL ACETATE	182	49.5	1337	1338
3-METHOXY-1-BUTYL ACRYLATE	183	49.6	1338	1338
M-DIETHYLBENZENE	177	49.8	1331	1339
ET GLYCOL DIBUTYL ETHER	204	51.8	1359	1348
P-DIETHYLBENZENE	187	52.9	1341	1353
3-ETHOXY-1-PROPANOL	204	53.1	1358	1354
3-METHOXY-1-BUTANOL	200	53.2	1355	1354
5-NONANONE	185	54.6	1340	1360
CYCLOHEXANONE	166	54.7	1319	1361
HEXYL ETHER	227	55.4	1379	1363
ETHYLIDENE DIACETATE	210	55.6	1364	1364
2-CHLOROETHANOL	198	56.2	1353	1367
4-HYDROXY-4-ME-2-PENTANONE	202	57.0	1357	1370
O-DIETHYLBENZENE	204	57.5	1359	1372
2-ALLYLOXYETHANOL	226	59.3	1376	1379
HEPTYL ACETATE	232	60.8	1383	1385
1-ETHOXY-3-PENTANOL	233	61.3	1384	1387
2-BUTOXYETHANOL	243	62.9	1392	1393
BIS(2-ETHOXYETHYL) ETHER	256	63.0	1402	1393
2-OCTANOL	252	62.9	1399	1393
CYCLOHEXANOL	238	64.1	1388	1397
CYCLOHEXYL ACETATE	211	64.2	1365	1397
4,4-DIMETHOXY-2-BUTANONE	243	64.6	1392	1399
TETRADECANE	253	64.9	1400	1400
2-ETHYL-1-HEXYL ACETATE	247	66.4	1396	1405
2-ETHYL-4-METHYL-1-PENTANOL	274	67.6	1415	1410
2-METHYLCYCLOHEXANOL	255	68.7	1402	1413
METHYLENE DIACETATE	357	69.3	1466	1415
2-NONANONE	240	70.7	1390	1420
2,4-HEXADIENAL	254	72.8	1401	1426
HEPTANOL	304	74.1	1435	1430
ACETONYL ACETATE	314	75.[illegible]	1442	1434
DIBUTYL CROTANAL	346	76.9	1460	1439
2-ETHYL-1-HEXYL PROPIONATE	345	80.7	1460	1450
2,3-DIMETHYL-2,3-BUTANEDIOL		81.3		1452
2-ETHYL-1-HEXANOL	379	84.4	1478	1460
2-METHYL-1,2-PROPANEDIOL		94.1		1485
ETHYLENE DIFORMATE	399		1488	
2-ETHYL-1-HEXYL ACRYLATE		97.5		1494
D,L-2,3-BUTANEDIOL		100		1500
2-ETHYL-2-HEXEN-1-OL		108		1518
4-ACETOXYTETRAHYDROPYRAN	466	111	1516	1524
OCTANOL	534	112	1545	1526
MESO-2,3-BUTANEDIOL		112		1526
4-HYDROXY-2-BUTANONE	470	114	1520	1530
ETHYLENE DIACETATE	506	120	1534	1542
1,2-PROPANEDIOL		121		1544
TRIMETHOXYMETHYLAL	561	134	1554	1560
1,3-HEXANEDIOL		143		1582
2-METHYL-2,4-PENTANEDIOL		143		1583
1-HYDROXY-2-ME-3-BUTANONE	641	146	1580	1587
ETHYLENE GLYCOL		147		1588
1,3-BUTYLENE DIFORMATE	630	150	1576	1594
HEXADECANE	710	154	1600	1600
1,2-BUTANEDIOL		177		1633
2,4-PENTANEDIOL		181		1637
NONANOL	906	181	1648	1638
1,3-BUTANEDIOL		228		1692
3-METHYL-2,4-PENTANEDIOL		254		1717
1,3-PROPANEDIOL		270		1731
2,2-DI ME-1,3-PROPANEDIOL		291		1749
2,4-HEPTANEDIOL		358		1797
OCTADECANE	1960	362	1800	1800
2-METHYL-1,3-PENTANEDIOL		384		1814
1,4-BUTANEDIOL		469		1861
DIETHYLENE GLYCOL		595		1917
1,5-PENTANEDIOL		742		1970
2-BUTEN-1,4-DIOL		774		1993
3-METHYL-1,5-PENTANEDIOL		966		2022
1,2-OCTANEDIOL		987		2025
1,6-HEXANEDIOL		1154		2051

Table 31 (cont.)

Note: V_g = retention volume of carrier gas.

I_x = Kovats index.

Data are for constant temperature runs at 120 or 160°C. For temperature-programmed runs the Kovats indices will be slightly different.

Table 32

MAJOR ODOROUS CONSTITUENTS OF VAPOR SAMPLES FROM PRESSED CRACKLINGS [1]

Consecutive Peak Number[2]	Type of Column Used	
	SP-1000 [3]	Pennwalt 223 [3]
1	Ammonia, trimethylamine, acetone (possible), n-pentene (butanal also possible), saturated C_6 hydrocarbon or pentanal, saturated C_7 hydrocarbon	Ethane (Kovats 200)
2	Heptene (?), C_8 hydrocarbon (?)	Ammonia, ethylene
3	Methanol (?), methyl ethyl ketone, saturated C_9 hydrocarbon	Propene
4	Ethanol, benzene, unsaturated C_7 hydrocarbon, dimethylpentadiene (1-heptyne also possible), (5-methyl-2-hexyne also possible)	Isobutene
5	1-Propanol (acetic acid possible), toluene	Trimethylamine
6	2-Methyl-1,3-pentadiene (?), ethylvinyl ether (?)	n-Pentane (500)
7	Xylenes, tricyclene	Acetone
8	A C_7 hydrocarbon (diene,-yne or cycloalkene), a C_8 hydrocarbon or C_7 ketone (eg. 2-heptanone)	n-Hexane (600)
9	A C_{10} alkyne or diene or substituted cyclohexene	2-Methyl propanal

Table 32 (cont.)

Consecutive Peak Number [2]	Type of Column Used	
	SP-1000 [3]	Pennwalt 223 [3]
10	1,3,7 Octatriene-5-yne(but could also be styrene on cyclooctatetraene	Tetrahydropyran, 2-Methyl furan (947)
11	Butyne-ol (?), C_4 substituted benzene	3-Methyl-hexane (possibly n-heptane)(700)
12	Dimethyl pyrazine	n-Pentanal
13	1-Hexanol	Trichloroethylene
14	Dimethyl ethylpyrazine (methoxy benzaldehyde somewhat possible)	Saturated C_8 hydrocarbon (probably (800) 2,4-dimethylhexane or 3-methylheptane or n-octane, unsaturated C_7 hydrocarbon or a C_6 aldehyde.
15	Hexyne-ol ?	Dimethyl disulfide (1110)
16	Hexadiene (?), benzaldehyde	Toluene
17	An alcohol (C_7 or C_8 possible)	2-Methyl furan (?)
18	Methyl naphthalene	Spectrum too complex
19	Dimethyl naphthalene, biphenyl	Spectrum too complex
20	Acenaphthene	Spectrum too complex

[1] Identified by GC-MS techniques; [2] Given in order of elution from the respective column;

[3] The question mark designates a non-positive identification.

Table 33

MAJOR ODOROUS CONSTITUENTS OF VAPOR SAMPLES FROM COOKER LIQUID[1]

Consecutive Peak Number [2]	Type of Column Used	
	SP-1000 [3]	Pennwalt 223
1	Ethanol	Trimethylamine
2	Propanol, 2-ethylbutonic acid (?), toluene	An alcohol
3	Methyl butanol	An amine
4	Butenal (?)	Carbon dioxide, an amine
5	Butanol	Nitrogen containing compound
6	1-Pentene	An amine
7	Hexanol	Spectrum too complex
8	Xylene	Spectrum too complex
9	Furfuryl alcohol (?)	Spectrum too complex
10	Possibly phenol, too weak to be sure	Spectrum too complex
11	p-Cresol or benzyl alcohol	Spectrum too complex

[1] Identified by GC-MS techniques; [2] Given in order of elution from the respective column;

[3] The question mark designates a non-positive identification.

plants. The odorous peaks were also described, and this information is summarized in the first few columns of Table 34. An asterisk indicates the most significant odorous peaks, while a plus sign indicates other significant odorous peaks.

10.4 Third Mass Spectrometer Identification Series

An additional series of mass spectrograph-chromatograph experiments was done on two samples obtained from a local rendering plant. Both the air from the press and the air after the cooker condenser were sampled. The objective was to identify the compounds responsible for the major odorous peaks previously established by panel tests. This work was done using a 10-ft SP-1000 column. Improved experimental techniques resulted in identification of additional odorants. The results are summarized in Table 30.

These mass spectrograph identifications were far more successful than any previously done and most of the odorous peaks appear to be identified. The following sulfides were found to be important: methyl sulfide, methyl disulfide, and propylene sulfide. The following nitrogen compounds were found to be important: trimethylamine, butylamine, quinoline, dimethyl, methylethyl, and trimethyl pyrazines. Other peaks with amine-like odors were not identified. A number of C_4 to C_7 aldehydes, ketones, and alcohols were also found, but specific compounds could not be definitely identified due to interference of hydrocarbons present. Acids were not identified, although several odorous peaks occur at Kovats indices where acids are expected. The acids may have been present in too low concentrations for the mass spectrometer. Several acids were tentatively identified in the first project. Butyric acid was included as one of the odorants being studied.

Table 34

IDENTIFICATION OF MAJOR ODOR COMPONENTS IN RENDERING ODORS

	Important Odorous Peaks				Mass Spectrometer Identification		Other Possibility	
Odor Note	Time, sec	Odor Panel Regression	Peak No.	Kovats Index	Kovats Index	Compound	Kovats	Compound
Sulfide	30		52		830	Dimethyl sulfide		
Grassy	237		16	1062	1010	Pentanal		
Sulfur	236	*	18	1073	1035-1105	Dimethyl disulfide		
Sulfur	173	+	20	1028	970	(A sulfur compound)		
Cabbage	880	*	14	1325	1370	(Dipropylene sulfide)		
Sour	52		50	804	800 880	Trimethylamine C_4 Aldehyde		
Yeast	53		44	804	800	Vinyl butyl ether		
Amine	107		26	933				
Amine	107		28	1028	980	(An amine)	950	(Butylamine)
Amine	248	+	36	1070	1015	(Butanedione)		
Amine	303		30	1115			1112	(Isobutylamine)
Amine	374		32	1161				
Amine	447		34	1187				
Oil	131		38	984	945-1000	Benzene		
Refinery	538		24	1227	1210	C_3 Benzene		
Burnt	1233	+	40	1440	1390 1470 1510	(Dimethyl pyrazine) (Trimethyl pyrazine) (Dimethyl-ethyl-pyrazine)		
Rendering	1335	+	22	1488	1410	(Nonadienal)	1570	(Butyric acid)
Burnt	1687	*	42	1618	1700 1660	Quinoline (A sulfur compound)		
Bitter	655	+	46	1251			1205	(Heptanol)
Unpleasant	474		56	1201	1150	(A sulfur compound)		
Unpleasant	1860	*	54	1634	1620	Me-indole or -indene	(1650)	(Isovaleric acid)
Cheesy	2002	+	48	1686			1690	(Valeric acid)
Unpleasant	2582	+	58	1812			(1810)	(Hexanoic acid)
Popcorn	810		60	1306	1260	Difurfuryl ether		

NOTE: Tentative identifications are in parentheses. Estimated Kovats indices are in parentheses.

* indicates most significant odorous peaks + indicates other significant odorous peaks

APPENDIX A

REFERENCES

A. Rendering Industry

A-1 Air Pollution Aspects of the Inedible Rendering Industry, Walsh, Robert T., J. of the Air Pollution Control Assoc., Feb. 1967, 17(2), 94-7.

> Informative Report No. 7 on the inedible rendering industry is one of a series of survey reports prepared by APCA's T1-2 Committee on air pollution problems and control methods encountered in the chemical industry today.

A-2 Air Pollution Engineering Manual, APCD of Los Angeles County, US Public Health Service Publication No. 999-AP-40, 1967.

> Contains a description of the rendering process and of the standard odor control methods, as well as design rules-of-thumb.

A-3 Odor Sources and Odor Control Systems in the Rendering Industry, Faith, W. L., Report to Fats & Proteins Research Foundation, Inc., 1967.

> Discusses sources of odors in rendering plants, odor prevention methods, and odor control methods.

B. Novel Methods

B-1 Efficiency of a Chemical System for Removing an Offensive Odor from a Bonemeal Fertilizer Plant, Muranaka, Hiromu; Hashimoto, Hiroshi; Araki, Kazuo; Ioku, Tsuneo; Yamamoto, Akira; Tatsumi, Teruo; Tsuchida, Tadafumi; Konishi, Kazuya; Ikeda, Hiroshi (Hokensyo, Osaka, Japan). Kagaku To Kogyo (Osaka) 1970, 44(6), 314-17 (Japan).

> The source of the odor from the plant was an autoclave for steaming animal bones and the pans for concentration of the glue solution. Compared with other systems, such as washing with water and adsorption by resin or activated C, a contact reaction by alkali (NaOH, $Ca(OH)_2$, etc.) and by acid (sulfuric, oxalic) was suitable.

B-2 Odor Abatement in the Rendering and Allied Industries, Teller, A. J., J. of the Air Pollution Control Assoc., April 1963, 13(4), 148-9, 166.

B-3 Prevention of Offensive Odor from Fish Processing Plants. II. Effect of Enzymes and Nitrohumic Acid Treatments on Reduction of the Odor from Squid Waste, Motohiro, Terushige; Terachi, Hitoshi (Fac. Fish., Hokkaido Univ., Hakodate, Japan). Hokkaido Daigaku Suisan Gakubu Kenkyu Iho 1969, 20(2), 134-41 (Japan).

A study was made to reduce the offensive odor from squid waste: proteinase activity is highest at 30-50° to decompose nitrogenous compounds in the waste leading to odor evolution. The odor can be absorbed in diatomaceous earth. Cellulase and amylase can also digest the waste, but their activities are lower than that of proteinase. Nitrohumic acid can control ammoniacal odor of the putrid smell at 0.5-2.0% level, but is unable to control the acid smell evolved from decayed waste. Application of nitrohumic acid to a waste containing high oil would be an improper way to prevent malodor.

C. General Discussions

C-1 Catalytic Afterburning of Industrial Gases, Betz, E. C. and Feist, H. J. (KAVAT Co., Gondsroth, Ger.), Technik (Berlin) 20(6), 395-401 (1965) (Ger).

A survey is given of the chemistry and technology of the treatment of gases containing hydrocarbons and N oxides mixtures. Translation available.

C-2 Controlling Industrial Odors, Yocom, John E., Chem. Eng., June 15, 1970, 160-8.

Industrial odors can be handled as chemical engineering problems; the key is to reduce the concentration of odorants at the receptor, i.e., the nose.

C-3 Incineration of Process Wastes, Frankel, Joseph I., Chem. Eng. 73(18), 91-6 (1966) (Eng.).

The disposal of industrial wastes by incineration is discussed. Equipment designed for solid, liquid, and gaseous wastes is described.

C-4 Industrial Odor Control., Turk, Amos (City Coll., City Univ. of New York, New York, N.Y.), Chem. Eng. (New York), 1969, 77(9), 199-206 (Eng.).

In this survey, the accepted methods of odor control are reexamined with emphasis on the inaccuracies and uncertainties which occur in practice. The discussion includes: the validity of outdoor dilution calculations; the measurement of odors by the dilution-to-threshold technique; the role of particulate matter; odor threshold variability; air oxidation; activated C adsorption; counteraction; and masking.

C-5 Industrial Odor Control and Its Problems, Turk, Amos, Chem. Eng., Nov. 3, 1969, 70-8.

In this discussion, therefore, I shall reexamine some of the accepted methods of odor control, with special emphasis on what can go wrong either in the methods themselves or in our assumption about how much control is necessary.

C-6 Methods of Air Deodorization, Summer, W., Elsevier, 1963.

General discussion of odor control methods.

C-7 A New Job for the Perfume Industry: Industrial Odor Removal, Sherwood, P. W., Parfum., Cosmet., Savons 5, 390-3 (1962).

The principal methods used in the elimination of industrial odors, including catalytic combustion, absorption and adsorption, and the use of masking agents and deodorizers, are described.

C-8 Odor Control at a 2,4-D Production Plant, Henshaw, T. B., J. of the Air Pollution Control Assoc., Nov. 1965, 15(11), 516-8.

Chlorinated phenolic hydrocarbons are used as intermediate chemicals in the manufacture of 2,4-D (2,4-Dichlorophenoxy-acetic Acid) and related herbicides. These chemicals have an unusual odor with an extremely low threshold level of detection and consequently the manufacture and handling of these compounds poses a difficult odor control problem. Chipman Chemical Company at its Portland, Oregon, plant has developed a system of fume collection and caustic soda solution scrubbing capable of removing phenolic compounds in the plant exhaust air to an acceptable level from an odor release standpoint. This article describes the development, present status, and projected future improvements of this odor control system.

C-9 Off-Gas Deodorizing, Palczynski, Ryszard; Glowiak, Bohdan (Politech. Wroclaw, Wroclaw, Polant), Gaz. Woda Tech. Sanit., 1968, 42(5), 157-60 (Pol.).

A survey is given of deodorization of off gases in industry. No new material.

C-10 Prevention of Pollutant Odors Caused by Organic Compounds, Franzky, Ulrich (Landes Nordrhein-Westfalen, Essen, Ger.), Staub, Reinhaltung Luft 1968, 28(3), 113-9 (Ger).

A detailed discussion is given of the different methods used for controlling odors from industrial processes, particuarly the chemical industry. The methods include thermal and catalytic combustion, ozonolysis, scrubbing in packed columns, and adsorption on activated carbons in continuous systems.

C-11 The Technology of Gas Cleaning: State of the Art., Hall, H. J., Trans. N.Y. Academy of Sciences, 147-64.

This paper reviews technology which is available and proven for controlling particulate emissions from stationary sources. In view of the importance of and legislative pressure for reducing sulfur oxide emissions, the state of the art of controlling this source of pollution is discussed in reasonable detail.

C-12 Use of Packed Beds for Separation of Entrained Particles and Fumes from an Air Stream, Eckert, John S., J. of the Air Pollution Control Assoc., Feb. 1966, 16(2), 95-8.

This paper deals with packed beds in discussion of separation of entrained particles and fumes from an air stream. Packed beds develop between the gas and liquid a maximum of contact in order to get maximum mass transfer from a gas to a liquid phase, and they are considered to be one of the better methods of scrubbing contaminants from a gas stream.

D. Design Data

D-1 Absorption of Chlorine in Water, Vivian, J. E.; Whitney, R. P.; Chem. Eng. Prog. 1947, 43(12), 691, 693.

Results of a study of the absorption of chlorine in water to produce bleach for pulp-mill operations are presented.

Chlorine absorption, because of low solubility, is expected to be a case of liquid film controlling. This is confirmed by the findings that the coefficient varies as the 0.6 power of the liquor rate and the 6th power of the absolute temperature, and is independent of the gas rate. These coefficients are lower than those predicted by the Sherwood and Holloway correlation, and an explanation of this lack of agreement, based on the relative rates of hydrolysis and of diffusion, is offered.

A pseudocoefficient, using an unhydrolyzed chlorine driving force, is proposed, and its relation to predicted values is discussed.

D-2 Catalytic Afterburning of Industrial Waste Gases--Its Basis and Technical Application, Gerhard Vollheim (Degussa Branch Office, Hanau, Ger.), Dechema Monograph, 52(895-911), 203-17 (1964) (Ger.).

By using suitable catalysts, such as Pt metals on metallic, ceramic, or oxide supports, base-metal oxides on oxide supports, the afterburning of organic waste gases from industrial processes can be carried out at 250°. The advantages and disadvantages of the various types of catalysts can be assessed from molecular-kinetic considerations. Practical examples are cited in which the process has already proved itself.

D-3 Concentration and Recovery of Atmospheric Odor Pollutants Using Activated Carbon, Brooman, David L.; Edgerley, E. Jr.; J. of the Air Pollution Control Assoc., Jan. 1966, 16(1), 25-9.

Activated carbon filters were used to concentrate atmospheric mixtures of acrolein, methyl sulfide, and n-propyl mercaptan. Removal efficiency and carbon capacity for each of the odor compounds were investigated using two different carbons, Cliffchar (4-10 mesh) and Barnebey-Cheney (C-4). A closed system was devised to establish a known atmospheric odor concentration for each filter run. Solvent extraction techniques were employed to desorb and recover the odor compounds from the carbon filters. All quantitative analyses were conducted with gas liquid chromatography utilizing the hydrogen flame ionization detector. The removal studies conducted indicate that the efficiency of removal of a carbon filter is essentially 100% up to the point of filter breakthrough. This breakthrough point is governed by the filter's capacity for a particular compound. This study indicated that the filter capacity is dependent both on the type of carbon employed and the particular odor compound adsorbed. Solvent recovery of the odor compounds from the carbons varied from 0 to 4.5% for the mercaptan up to 96 to 98% for acrolein. Percent recovery was found to vary for a given odor compound with different carbons and for a given carbon with different odor pollutants.

D-4 The Design and Performance of a Bootstrapping Direct Flame Afterburner, Ridgway, S. L.; Lair, J. C.; J. of the Air Pollution Control Assoc., July 1962, 12(7), 340-7.

D-5 Efficient Design of Afterburners for Incineration of Many Industrial Fumes, Crouse, Lowell F.; Waid, Donald E.; Air Eng., 9(8), Aug. 1967, 20-3, 29.

Combustion methods to remove organic or C-containing substances from gaseous effluent streams are reviewed. The two general combustion methods involve catalytic oxidation and direct flame incineration in an afterburner. Designs of industrial direct flame incineration equipment are discussed. Quantitative data are given comparing the performance of a single-burner tunnel-type burner and the Combustifume Burner. For example, to obtain an outlet stream containing 30 ppm hydrocarbons an average temperature of 1450°F is required in a tunnel-type single burner while in the Combustifume line burner, a temperature of 1130°F is required.

D-6 Energy and Efficiency Characteristics of the Ejector Venturi Scrubber, Harris, L. D., J. of the Air Pollution Control Assoc., July 1965, 15(7), 302-5.

The scrubbing and pumping actions in the Ejector Venturi Scrubber are two separate phenomenon occurring simultaneously. Each phenomenon requires energy and has efficiency of operation and collection efficiency. These energy and efficiency relationships are discussed and illustrated in the form of numerous graphs. The scrubbing energy requirements and how they vary with particle sizes down to one micron are also discussed and presented in the form of numerous graphs.

D-7 An Evaluation of Catalytic and Direct Fired Afterburners for Coffee and Chicory Roasting Odors, Sullivan, J. L.; Kafka, F. L.; Ferrari, L. M.; J. of the Air Pollution Control Assoc., Dec. 1965, 15(12), 583-6.

Though the aroma of roasting coffee can be pleasant in small amounts, large scale plants tend to cause public complaints. As a means of control thermal afterburners operating at 1200°F and higher have been commonly employed. Australian coffee consumption in the past has been relatively small but in recent years it has been increasing markedly. As a result, odor complaints have been increasing and one plant, large by Australian standards, caused a public outcry of no small order. High cost of fuel rendered thermal afterburning unattractive and, consequently, the firm in question decided upon catalytic combustion as an alternative. Subsequently, the unit was installed and before and after tests were made for various components. At an operating temperature of about 700°F the results showed comparable fume reductions to thermal afterburning and the findings were confirmed by the cessation of complaints by the public.

D-8 Fume Control in Wire Enameling by Direct-Flame Incineration, Benforado, David M.; Waitkus, Joseph; J. Of the Air Pollution Control Assoc., Jan. 1968, 18(1), 24-6.

The results of source tests to demonstrate the applicability of direct-flame incineration for the control of the effluent from a wire-enameling bake oven are presented. The tests were conducted with a portable direct-flame incinerator under actual plant conditions. The efficiency of direct-flame incineration was established at incineration temperatures of 1000°F, 1200, and 1400°F. Evaluation of incineration efficiency was performed by both analysis and quantitative odor measurement using an odor panel.

D-9 Fume Incineration with Combustion Air at Elevated Temperature, Meyers, F. D.; Waitkus, Joseph; J. of the Air Pollution Control Assoc., July 1966, 16(7), 378-82.

The description of a unique system for the decomposition of objectionable fumes, applied for air pollution control to a fiber glass curing oven. The investigations preceding the development of the system are covered, followed by a description of the principal components of the system combining recuperative and regenerative heat exchange to produce a combustion air temperature appreciably above ambient.

D-10 Gas Absorption in Beds of Rings and Saddles, Leva, Max, A.I.Ch.E. Journal, 1(2), 224, 225, 1955.

New data are presented for the system carbon dioxide-sodium hydroxide. The effect of $CO_3^{=}$ buildup upon K_Ga values was investigated first and the data were then used to construct a curve by means of which all data were corrected to an arbitrarily chosen reference state of 25% $CO_3^{=}$ concentration. K_Ga values increased with increasing liquid rate but were not dependent on gas rate if the packings were operated below loading. For some packings examined in the loading range, however, K_Ga values increased with increasing gas rate.

K_Ga values examined in relation to specific surface area were found to be very irregular in connection with rings. The surface-area utilization pattern of the saddles was considerably more uniform. The ring and saddle data for the carbon dioxide-sodium hydroxide system were in good qualitative agreement with the ammonia absorption data of Fellinger and the water-water vapor data of Mehta and Parekh.

D-11 Odor Control in Poultry By-products Rendering, A Case History, Industrial Standards Committee, National Renderers Assoc. Odor Control Manual, 1971.

Describes installation of a Peabody scrubber (impingement baffle plate) in a rendering plant. It seemed to control the odor.

D-12 Some Data and Observations on Combustion of Gaseous Effluents from Baked Lithograph Coatings, Wallach, Abraham, J. of the Air Pollution Control Assoc., Mar. 1962, 12(3), 109-10.

D-13 A Study of Catalyst Support Systems for Fume-Abatement of Hydrocarbon Solvents, Miller, M. R.; Wilhoyte, H. J.; J. of the Air Pollution Control Assoc., Dec. 1967, 17(12), 791-5.

In a stainless steel pilot plant system, operating with combined thermal incineration and catalytic oxidation, studies have been made of the influence of catalyst-support geometry on abatement efficiency. Catalyst supports tested were ceramic spherical pellets, metal foils, and ceramic honeycomb structures, all with precious metal catalyst. Data obtained cover a range of space velocities from 30,000 to 175,000 scf/hr-cu ft bed and a range of catalytic reactor temperatures from 150 to 450°C. Results show that optimum fume-abatement performance is obtained by combining incineration and catalytic oxidation and that catalyst support geometry has a significant effect on performance.

E. Design Methods

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E-2 Absorption Towers, Morris, G. A. and Jackson, J., Butterworths, 1953.

E-3 Chem. Engrs. Handbook, 4th Ed., Perry, J. H., (Ed.), McGraw-Hill.

E-4 Distillation, Van Winkle, Mathew, McGraw-Hill, 1967.

E-5 Mass Transfer and Absorbers, Hobler, T., Pergamon Press, 1966.

E-6 Mass Transfer Operations, Treybal, R. E., McGraw-Hill, 1967.

E-7 Mass Transfer Process Calculations, Sawistowski, H. and Smith, W., Interscience Publ., 1963.

E-8 Tower Packings and Packed Tower Design, Leva, Max, U.S. Stoneware Co., 1953, Akron, Ohio.

E-9 U.S. Stoneware Co., "Packed Tower Design Manual," Akron, Ohio.

E-10 Mass Transfer in Heterogeneous Catalysis, Satterfield, C. N., M.I.T. Press, 1970.

F. Cost Data

F-1 Air Pollution Manual Part II, Control Equipment, American Hygiene Association, Detroit, Michigan 48227, 1968.

Contains costs of control equipment.

F-2 Control techniques for Particulate Air Pollutants, US Public Health Service Publication AP-51, 1969.

Describes sources in various industries and gas cleaning devices. Gives extensive data on costs of equipment.

F-3 The Development of a Condenser for Odor Control from Dry Rendering Plants, Strauss, W., J. of the Air Pollution Control Assoc., Oct. 1964, 14(10), 424-6.

A new surface condenser and carbon adsorber has been developed which provides an economical solution to the problem of odors from dry rendering plants.

F-4 Fume Control in Rubber Processing by Direct-Flame Incineration, Sandomirsky, Alex G.; Benforado, David M.; Grames, Lloyd D.; Pauletta, Carl E.; J of the Air Pollution Control Assoc., Dec. 1966, 16(12), 673-6.

The application of direct-flame incineration to successfully eliminate a smoke-oil-mist and odor problem in the manufacture of rubber-base rug underlay, is presented. The investigation of various air pollution control processes leading to the development and adoption of the direct-flame incineration system, is covered. The rug-underlay curing process incorporating the direct-flame incineration system with primary heat recovery is described. Results and discussion of a source test to determine the effectiveness of direct-flame incineration in this application are included.

F-5 Fume Incineration, Brewer, Gerald, L., Chem. Eng. Oct. 14, 1968, 160-5.

Direct flame, thermal or catalytic incineration may be the most economical way to remove odor-causing gases and vapors from chemical processes. Success in coming up with the most effective and lowest cost system rests in thorough consideration of design parameters.

F-6 Odor Control by Catalytic and High-Temperature Oxidation, Hein, Glen M. (Battelle Mem. Inst., Columbus, Ohio), Ann. N.Y. Acad. Sci. 116(2), 656-62 (1964.

Direct-flame and catalytic combustion, the odor-laden effluent, together with sufficient air for combustion, is fed into a gas- or oil-fired combustion chamber where proper conditions of temperature, time, and turbulence are provided. The direct-flame afterburner method is ideally suited for the control of residual odors from small and medium size refuse incinerators that are operated intermittently. With such incinerators, the exhaust gases are already hot, and auxiliary fuel is fired to maintain temperatures required for destruction of odor in the afterburner, which is an integral part of the refuse incinerator. Combustion with air on catalyst surfaces reaches completion at much lower temperatures than those required for conventional flame burning. At lower temperatures combustion is flameless. The oxidation catalysts used in odor control applications are Pt alloys or a combination of Pt and Al_2O_3.

F-7 Odor Control in Rendering by Wet Scrubbing - A Case History, Anderson, Leonard W., Carolina By-Products Co., National Renderers Assoc. Odor Control Manual, 1971.

Cost data on a specific wet scrubber installation.

F-8 Plant Design and Economics for Chemical Engineers, Peters, M. S. and Timmerhaus, K. P., McGraw-Hill, 1968.

F-9 Study of Costs of Non-condensable Fume Incinerators for Rendering Plant Effluents, Heilman, Bill, National By-Products, Inc., Des Moines, Iowa, 1970, National Renderers Assoc. Odor Control Manual, 1971.

Contains calculated cost comparisons for fume incinerators with and without heat exchangers.

F-10 Tellerette Manual, Ceilcoate Co., 140 Sheldon Road, Berea, Ohio 44017.

G. Experimental Apparatus

G-1 Chemical Reactions on a Rotating Disk., Litt, M. and Serad, G., (Univ. of Pennsylvania, Philadelphia), Chem. Eng. Sci. 19(11), 867-84 (1964) (Eng.).

A model for a 2-component, rapid chemical reaction for the case of laminar flow on a rotating disk was developed. Data were obtained for dissolution of benzoic acid (I), cinnamic acid (II), and β-naphthol (III) in H_2O; of reaction of I with aqueous NaOH; and for dissolution of napthalene in air. The data agree with theory except for II and III. The rotating disk system is recommended for fundamental investigations of combined transport and reaction.

G-2 Kinetics of Liquid-Film Process in Gas Absorption. Part I: Models of the Absorption Process, Danckwerts, P. V.; Kennedy, A. M.; Trans. Instn. Chem. Engrs., 1954, 32, Supplement, 49-2.

Three models of the processes involved in the absorption of gas into agitated liquids are compared. These are: steady-state diffusion through a stagnant film; transient absorption into surfaces which are systematically replaced by fresh liquid; and transient absorption into surfaces which are randomly replaced. It is shown that the three models lead to closely similar predictions about the effect of physico-chemical variables (solubility, diffusivity, reaction rate, etc.) on the rate of absorption.

Hence if one of the models is correct the effects of changes in these variables will not distinguish between them, but on the other hand the formulae derived for any of the models can be used for prediction.

G-3 Kinetics of Liquid-Film Processes in Gas Absorption. Part II. Measurements of Transient Absorption Rates, Danckwerts, P. V.; Kennedy, A. M.; Trans. Instn. Chem. Engrs., 1954, 32, Supplement, 53-9.

Values of the physico-chemical quantities discussed in Part I are often not available, and are difficult or impossible to measure. The second and third models considered do not require explicit knowledge of these quantities, but only measurements of transient rates of absorption for short times of contact between gas and liquid. Such transient rates have been measured in an apparatus incorporating a rotating drum. Carbon dioxide was absorbed into water, solutions of salts, buffer solutions and sodium hydroxide solution. Times of exposure were less than 0.25 sec. Comparison with rates of absorption in a packed column suggests that none of the three models gives an adequate descritpion of the absorption process.

There is prima facie evidence of a substantial surface resistance to the absorption of carbon dioxide in water.

G-4 Liquid Phase Mass Transfer Rates and Effective Interfacial Area in Packed Absorption Columns, Fumitake Yoshida; Tetsushi Koyanagi; Ind. and Eng. Chem., Mar. 1958, 50(3), 365-7, 368.

The present work was intended to obtain a more general correlation for liquid phase mass transfer rates in packed columns. Studies were made on the absorption of pure carbon dioxide into water and methanol in a column packed with spheres, Raschig rings, and Berl saddles as well as in a bead column containing spheres connected in a vertical row. Reasonable correlations among the height of a transfer unit, the Reynolds number, and physical properties of the liquid phase were obtained. The effective interfacial area in the packed column and its variation with liquid rates were determined for both water and methanol.

G-5 Mass and Heat Transfer from an Enclosed Rotating Disk With and Without Source Flow, Kreith, Frank, Doughman, E., and Kozlowski, H. (Univ. of Colorado, Boulder), J. Heat Transfer 85, 153-63 (1963).

The heat-transfer characteristics of a partly enclosed rotating disk were investigated experimentally by means of a mass-transfer analog. Mass-transfer rates to air from naphthalene-coated disks 4 and 8 in. in diameter were measured at 0-10,000 r.p.m., and the effect of the spacing between the rotating disk and its housing was studied with and without source flow. From the experimental results a dimensionless correlation equation suitable for predicting average heat- and mass-transfer coefficients for rotating disks with source flow in turbulent flow at rotational Re up to 4 x 10^5 was deduced. The flow pattern was studied with a hot wire, a smoke visualization technique, and the china clay method.

H. Odor Analysis

H-1 Analysis of Odorous Gases Generated from Fish-Solubles and Fish Meals, Kuroda, Daisuke (Osaka-Shiritsu Kogyo Shikensho, Osaka, Japan). Kagaku To Kogyo (Osaka) 1969, 43(7), 367-70 (Japan).

To obtain the fundamental information to remove odorous gases generated from fish products, a 10-g sample was placed in a 500-ml flask and heated to 250° in increments of 5°/min. After trapping the high boiling decomposition products, the gaseous component was introduced into a gas chromatograph, with a 2-m column packed with dioctyl phthalate and analyzed at 120° column temperature with 50 ml/min H. Identification of peaks was done by comparison of retention times with standard substances and chemical identification of radicals by using a reaction tube packed with sodium nitroprusside, $Pb(OAc)_2$, or isatin, connected to the gas exit of the gas chromatograph. As standard substances, the compounds and these retention time (sec.) are given as follows: NH_3 (Ia), 47.8; Me_2NH, 67.5; Me_3N (II), 75.0; $EtNH_2$, 76.0; iso-$PrNH_2$ (IIIa), 108.0; n-$PrNH_2$ (IIIb), 127.5; Et_2NH (IV), 142.5; iso-$BuNH_2$ (Va), 165.0; n-$BuNH_2$ (Vb), 187.5; Et_3N (VI), 225.0; n-pentylamine, 247.7; n-Pr_2NH

(VII), 262.5; H_2S (Ib), 48.0, MeSH (VIII), 56.0; EtSH (IX), 95.0, iso-PrSH, 106.0; n-PrSH, 165.0; sec-BuSH, 179.0; n-BuSH, 290.0. From practical samples, only 9 peaks were separated as retention time of 48, 60, 75, 90, 114, 143, 180, 216, and 258. So these 9 peaks were identified as Ia + Ib, VIII, II, IX, IIIa or IIIb, IV, Va or Vb, VI, and VII, respectively. Relation between the peak heights and heating times or temperatures were also shown. In the case of fish-solutions, the order of peak area of these components was II > III > V > IV, but with fish-meal, it was II > IV > III > V.

H-2 Identification of Chemical Constituents in Rendering Industry Odor Emissions, IITRI Project C8172, Fats & Proteins Research Foundation, Inc.

Analytical studies conducted on rendering odor samples were based on both vapor samples gathered at the plant sites and on synthetic laboratory vapor samples prepared from solid plant samples. Odorous components were identified by a combination of gas chromatographic-olfactronic techniques coupled with mass spectrographic analysis. More than 30 components were identified and showed the presence of such classes of organic species as alkanes, aldehydes, ketones, aromatics, acidic and miscellaneous compounds. Analysis by gas chromatography-sulfur detection methods showed the presence of sulfur components in all samples studied. Threshold data on the components identified by mass spectrographic analysis are also reported.

APPENDIX B

ODOR CONTROL COST COMPARISONS

Comparative Costs for Catalytic and Flame Afterburner

	Operating Condition				Unit Costs, $/hr. per 1,000 cfm.		
Case No.	Extent of Waste Heat Recovered	Calorific Value of Odor Source Gas	Item of Cost		Catalytic Method	Direct-Flame Method	Cost Ratio Flame/Cat.
1	None	Nil	Fixed charges		$0.15	$0.10	
			Burner fuel		0.51	1.06	
			Maintenance		0.09	0.06	
			Labor		0.03	0.03	
				TOTAL	$0.78	$1.25	1.60
2	None	1/4 LFL	Fixed charges		$0.15	$0.10	
			Burner fuel		0.03	0.58	
			Maintenance		0.09	0.06	
			Labor		0.03	0.03	
				TOTAL	$0.30	$0.77	2.45
3	1/2 of Input	Nil	Fixed charges		$0.19	$0.17	
			Burner fuel		0.27	0.58	
			Maintenance		0.11	0.10	
			Labor		0.03	0.03	
				TOTAL	$0.60	$0.88	1.33
4	1/2 of Input	1/4 LFL	Fixed charges		$0.19	$0.17	
			Burner fuel		(−0.20)	0.10	
			Maintenance		0.11	0.10	
			Labor		0.03	0.03	
				TOTAL	$0.13	$0.40	3.10

(Ref. C-2)

The cost for the catalytic method is less than that of the direct flame method.

Comparative Costs of Direct-Flame Afterburners on Rendering-Plant Emissions With and Without Heat Recovery

System	Incineration Without Heat Recovery	Incineration with a Single-Pass-Primary and a Single-Pass-Secondary Heat Exchanger	Incineration with a Double-Pass-Primary and a Single-Pass-Secondary Heat Exchanger
Initial cost, $	16,750	42,300	58,800
Approximate erection, $	3,800	4,600	5,400
Hourly operating cost, $/hr.	4.33	2.58	1.84
Annual operating cost, $/yr.,= fuel cost minus makeup-air savings	25,900	13,510	9,630
Annual fuel savings for makeup air, $/yr.	None	1,960	1,370
Total system cost, $	20,550	46,900	64,200
Annual cost, including initial cost plus operating cost, based on 15-yr. life, $	27,270	16,630	13,910
Operating cost $/hr./1,000 cfm	.64	.38	.27

Notes:
Fuel cost 50¢/10^6 Btu.
Annual operating hours, 6,000.
Erection of incinerator only.

(Ref. C-2)

Heat recovery can cut the cost in half.

INCINERATOR WITH AND WITHOUT HEAT RECLAIM

Source: (Ref. F-9)

Mfg. - Air Preheater Co., Wellsville, New York
Detention - Min. 0.3 Sec. @ 1200°F
Temp. Range - Operating 1200-1400°F

Base - 50¢/MCF Natural Gas Cost @ 1000 BTU/cu.ft.
1.5¢/KW Electrical Cost

Unit 5-2 (*Fuel Rate Based on 2,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

Vol = 2000 (.3/60) = 10 ft^3

Heat Exchanger	%	None	35% Eff.	47% Eff.	59% Eff.
Flow Rate	SCFM	2,000	2,000	2,000	2,000
Equip. Cost	$	13,050	20,100	23,700	33,350
Est. Installed Cost	$	17,050	26,900	31,900	44,550
Fuel 10^6 BTU/Hr.	*	2.25	1.46	1.19	.92
Power	KW	3.0	3.5	3.75	6.5
Weight	#	7,600	13,000	15,600	21,720
Cost of Gas & Elct/Hr.	$	1.18	.78	.66	.56
Cost/1000 SCFM		59¢	40¢	33¢	28¢

Unit 5-5 (*Fuel Rate Based on 5,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

Vol = 25 ft^3

Heat Exchanger	%	None	35% Eff.	47% Eff.	59% Eff.
Flow Rate	SCFM	5,000	5,000	5,000	5,000
Equip. Cost	$	15,550	24,230	29,400	41,800
Est. Installed Cost	$	20,550	32,230	39,400	55,800
Fuel 10^6 BTU/Hr.	*	6.20	4.04	3.28	2.54
Power	KW	13.0	17.0	23.0	34.0
Weight	#	9,400	15,800	19,000	26,420
Cost of Gas & Elect/Hr.	$	3.30	2.28	1.99	1.78
Cost/1000 SCFM		66¢	46¢	40¢	36¢

Unit 8-9 (*Fuel Rate Based on 10,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

Vol = 50 ft^3

Heat Exchanger	%	None	39% Eff.	48% Eff.	64% Eff.
Flow Rate	SCFM	10,000	10,000	10,000	10,000
Equip. Cost	$	20,600	32,600	38,080	54,600
Est. Installed Cost	$	26,600	42,600	50,080	71,600
Fuel 10^6 BTU/Hr.	*	12.4	7.55	6.45	4.45
Power	KW	14.0	27.0	24.0	36.0
Weight	#	13,800	22,500	26,700	37,430
Cost of Gas & Elect/Hr.	$	6.41	4.19	3.59	2.75
Cost/1000 SCFM		64¢	42¢	36¢	28¢

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Unit 8-14 (*Fuel Rate Based on 15,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

V = 75 ft^3

Heat Exchanger	%	None	39% Eff.	48% Eff.	64% Eff.
Flow Rate	SCFM	15,000	15,000	15,000	15,000
Equip. Cost	$	24,750	36,780	43,980	62,000
Est. Installed Cost	$	31,750	47,780	57,980	82,000
Fuel 10^6 BTU/Hr.	*	18.6	11.3	9.65	6.7
Power	KW	23.0	62.0	58.0	80.0
Weight	#	15,300	25,300	30,600	42,730
Cost of Gas & Elect/Hr.	$	8.65	6.58	5.70	4.55
Cost/1000 SCFM		64¢	44¢	38¢	30¢

Unit 8-18 (*Fuel Rate Based on over 20,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

V = 100 ft^3

Heat Exchanger	%	None	39% Eff.	48% Eff.	64% Eff.
Flow Rate	SCFM	20,000	20,000	20,000	20,000
Equip. Cost	$	28,000	43,530	52,530	74,850
Est. Installed Cost	$	36,000	56,530	68,530	97,850
Fuel 10^6 BTU/Hr.	*	24.8	15.1	12.8	8.9
Power	KW	35	82	76	109
Weight	#	17,300	29,400	35,400	50,130
Cost of Gas & Elect/Hr.	$	12.93	8.78	7.54	6.09
Cost/1000 SCFM		65¢	44¢	38¢	31¢

Unit 8-28 (*Fuel Rate Based on 30,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

V = 150 ft^3

Heat Exchanger	%	None	39% Eff.	48% Eff.	64% Eff.
Flow Rate	SCFM	30,000	30,000	30,000	30,000
Equip. Cost	$	34,350	55,880	66,830	93,100
Est. Installed Cost	$	43,350	71,880	86,330	121,100
Fuel 10^6 BTU/Hr.	*	37.3	22.7	19.4	13.4
Power	KW	50.0	123	113	152
Weight	#	19,900	34,600	42,200	60,230
Cost of Gas & Elect/Hr.	$	19.40	13.20	11.40	8.98
Cost/1000 SCFM		65¢	44¢	38¢	30¢

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Heat recovery can halve the cost.

INCINERATOR PERFORMANCE DATA
vs
CONTRACT SPECIFICATIONS (TEST #4)
30 JULY 1970

	Result Test #4	Expected Based on Input of Test #4
Flow SCFM	28,900	28,900
#/hr	130,000	130,000
Temperature in (°F)	120	120
Air Temperature Out Cor-Pak (°F)	822	806
Incineration Chamber Temperature (°F)	1,203	1,203
Stack Temperature (°F)	550	555
System ΔP ("W.G.)	10.4	13.4
Heater Exchanger Effectiveness	64.8	63.3
Fuel Rate #/hr	600	642
Odor Units/SCF	<150	<150

ODOR EVALUATION RESULTS
AT
INCINERATION CHAMBER TEMPERATURES OF
APPROXIMATELY 1000, 1100, 1200, & 1400°F

.3 sec Contact Time

Incineration Chamber Temperature (°F)	Test No.	Odor Concentration Odor Units/SCF	
		Duct Inlet	At Stack Outlet
1007	2	1000	270
		1500	290
1100 (Nominal)	5	3000	395
		2500	1000
1203	4	3600	105
		4200	90
1400 (nominal)	7	3000	43
		3000	<10

Conclusion: At 1400°F reduction ratio is 70 to 300; and at 1100°F is 2.5 to 10.

OPERATING COST COMPARISON

Scrubber vs. Incinerator
(Spray Tower)

	Scrubber	Incinerator
Initial Cost - Installed	$40,000	$65,000
Capacity	60,000 cfm	25,000 cfm
Annual Operating Hours	3100 hrs.	2500 hrs.
Running H.P.	70 H.P.	30 H.P.
Estimated Actual Life	15 yrs.	8 yrs.
Annual Operating Cost		
1. Chemicals - Soda Ash 500 lb/wk @ 3.35¢ x 26 wks	$ 435.00	- -
2. Water 8200 gal/wk @ 60¢/1000 gal. x 26 wks	130.00	- -
3. Fuel $5.50/hr x 2500 hrs.	-	$13,800.00
4. Power H.P. x .7457 x $.009/KWH x Running Hrs.	1,450.00	500.00
5. Maintenance (estimated)	200.00	500.00
6. Labor (operational)	500.00	-
7. Amortization of Investment	2,670.00	8,120.00
Total Annual Operating Costs	$ 5,385.00	$22,920.00
Operating Cost/Hr	$1.74	$9.16
Operating Cost/Hr/1000 cfm	$ .03	$ .37

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(Ref. F-7)

The total annual cost of the incinerator is over 4 times that of the scrubber.

Comparison of Crossflow vs. Countercurrent

Energy Cost in Gas and Liquid Phase

Annual and First Cost of Installing Fan and Recycle Pump

With Motors

	Crossflow	Countercurrent
Energy Cost		
Fan - Gas Phase	$ 2,170	$ 4,380
Pump - Liquid Phase	595	4,680
Total Annual Energy Cost	$ 2,765	$ 9,060
Fan HP	41.5	84.0
Pump HP	11.5	90.8
Total HP req'd.	53.0	174.8
First Cost Fans @ 10¢/CFM	$ 9,500	$ 9,500
First Cost Pump @ $1.50/GPM	1,160	6,750
First Cost Motors @ $15.00/BHP	795	2,600
Electrical Installation Cost for: switches, motor starters, power wiring, control wiring, etc. @ $30/BHP	1,590	5,250
Total First Cost	$13,045	$24,100

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(Ref. F-10)

Cross-flow tower gives the smaller total cost.

Comparison of scrubber operating costs

Scrubber type	Liquid rate (g.p.m.)	Liquid pressure (p.s.i.g.)	Pump h.p.	Scrubber pressure drop (in. water)	Total pressure drop (in. water)	Fan h.p.	Total h.p.	Annual power cost
Cross flow								
Tellerette packing	50	5	0.3	0.5	1.5	4.3	4.6	$ 370
Berl saddle packing	60	5	0.4	1.2	2.2	6.3	6.7	540
Raschig ring packing	60	5	0.4	3.8	4.8	13.8	14.2	1140
Counter-current								
Tellerette packing	120	5	0.7	0.75	1.75	5.0	5.7	460
Berl saddle packing	140	5	0.8	2.2	3.2	9.1	10.0	810
Raschig ring packing	140	5	0.8	6.7	7.7	22.0	22.8	1840
Wet cyclone	80	60	5.6	3.5	4.5	12.8	18.4	1490
Spray tower	100	80	9.6	2.0	3.0	8.6	18.2	1470
Jet	600	60	42.0		1.0	none	42.0	3380
Venturi	80	20	1.9	15.0	16.0	46.0	47.9	3860

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(Ref. F-10)

Packed cross-flow tower gives the smallest power cost of the wet scrubbers.